No. 180-1

basic synchros and servomechanisms

by VAN VALKENBURGH,
NOOGER & NEVILLE, INC.

VOL. 1

SYNCHRO FUNDAMENTALS

SYNCHRO GENERATORS, MOTORS

SYNCHRO DIFFERENTIALS,
CONTROL TRANSFORMERS,

SERVO FUNDAMENTALS

DESIGNING YOUR OWN SERVO

RIDER

basic synchros and servomechanisms

by VAN VALKENBURGH,
NOOGER & NEVILLE, INC.

VOL. 1

JOHN F. RIDER PUBLISHER, INC., NEW YORK
a division of HAYDEN PUBLISHING COMPANY, INC.

L

First Edition

Library of Congress Catalog Card No. 55-11758

SEVENTH PRINTING 1963

Printed in the United States of America

PREFACE

What has been called "the Second Industrial Revolution"—automation or automatic process control—is an outgrowth of the technical advances made during World War II in military equipment. The heart of the automatic, electronically controlled mechanisms for this purpose is the subject of these two volumes dealing with synchros and servomechanisms.

Besides the wide application of these devices in all types of modern military equipment, business and industry are making rapid strides in the use of synchros and servomechanisms in automatic process control, as in chemical plants, oil refineries, steel, textile and paper mills, in the manufacture and assembly of automotive and electronic equipment; and in the processing of data (sales, inventory, production, payroll, etc.) in offices and laboratories.

The text of this Basic Synchros and Servomechanisms course, as currently taught at Navy specialty schools, has now been released for civilian use. This course is given to all Navy ratings whose duties require them to work with equipment which uses synchros and servomechanisms. It is a further extension of the background courses the trainee took in "Basic Electricity" and "Basic Electronics" (also by Van Valkenburgh, Nooger & Neville, Inc.). This educational program has been an unqualified success. Since April, 1953, when it was first installed, over 25,000 Navy trainees have benefited by the instruction and the results have been outstanding.

This set of two volumes on "Basic Synchros and Servomechanisms" follows exactly the same format and method of presentation employed for "Basic Electricity" and "Basic Electronics." The unique simplification of an ordinarily complex subject, the exceptional clarity

of illustrations and text, and the plan of presenting one basic concept at a time, without involving complicated mathematics, all combine in making this course a better and quicker way to learn (and teach) Basic Synchros and Servomechanisms.

Another purpose is to acquaint those in industry and government —from corporation president to newest apprentice—with the most basic facts concerning automation. As an example of how synchros and servomechanisms can replace the human brain in situations requiring uninvolved, routine procedures, you will go through, step by step, the designing of a simple servomechanism for the automatic steering of a ship. This could just as well have been the operation of a mixing valve in an oil refinery or a computer in an office.

In releasing this material to the general public, the Navy hopes to provide the means for creating a nation-wide pool of pretrained technicians, upon whom the Armed Forces could call in time of national emergency, without the need for precious weeks and months of schoolinig.

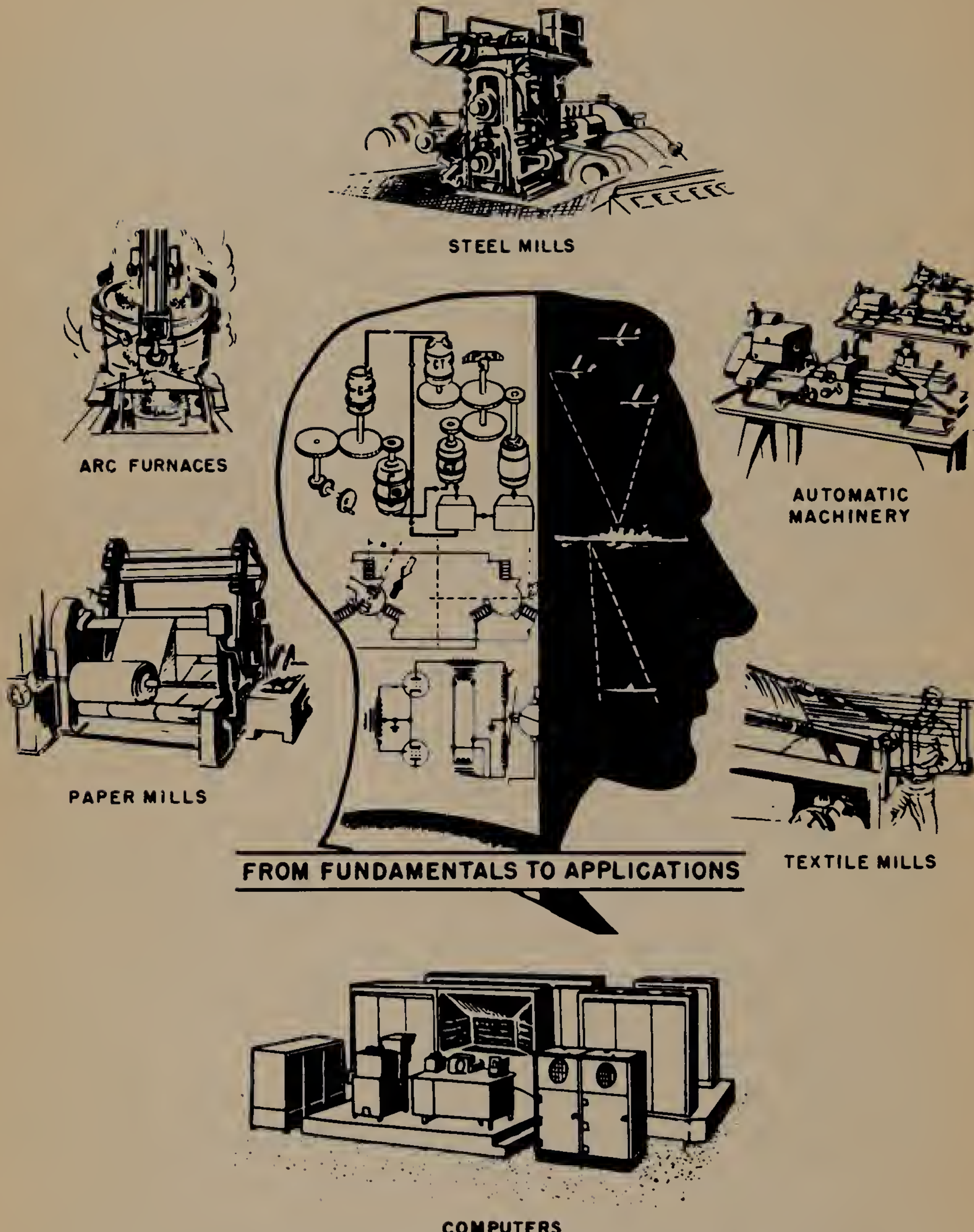
Perhaps of greater importance is the Navy's hope that through the release of this course, a direct contribution will be made toward increasing the technical knowledge of men and women throughout the country, as a step in making and keeping America strong.

New York, N. Y. *Van Valkenburgh, Nooger & Neville, Inc.*

August, 1955

TABLE OF CONTENTS

Vol. 1 — Basic Synchros and Servomechanisms

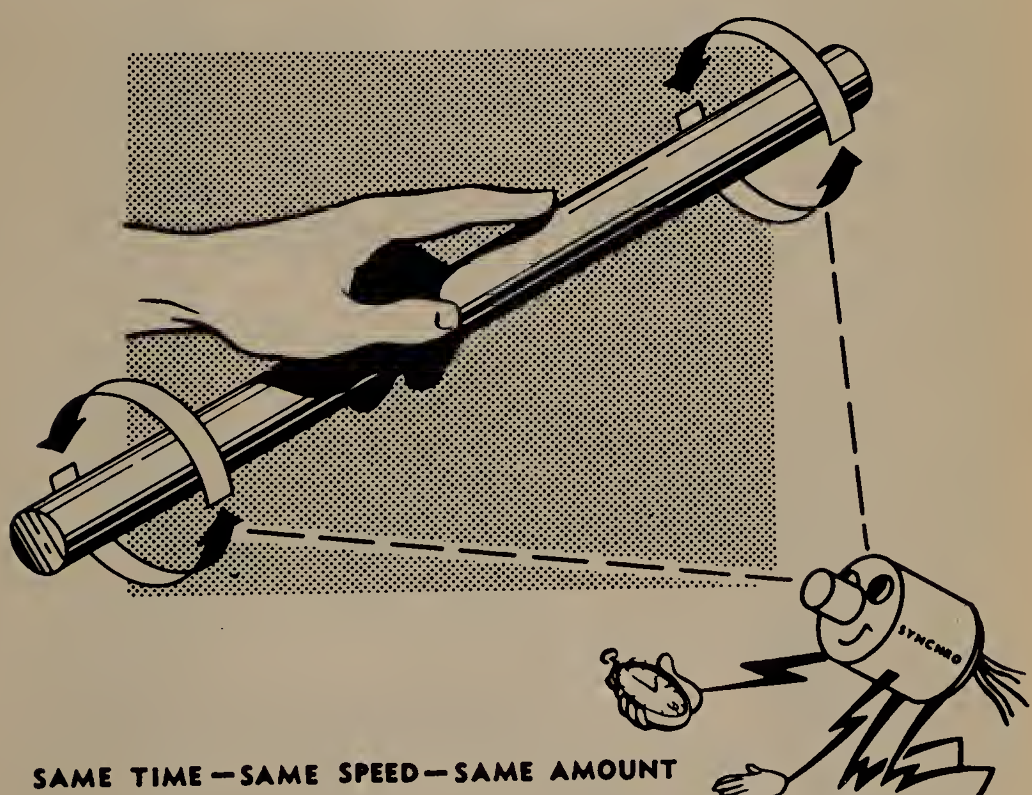


STEEL MILLS
ARC FURNACES
AUTOMATIC MACHINERY
PAPER MILLS
TEXTILE MILLS
FROM FUNDAMENTALS TO APPLICATIONS
COMPUTERS

What a Synchro Is

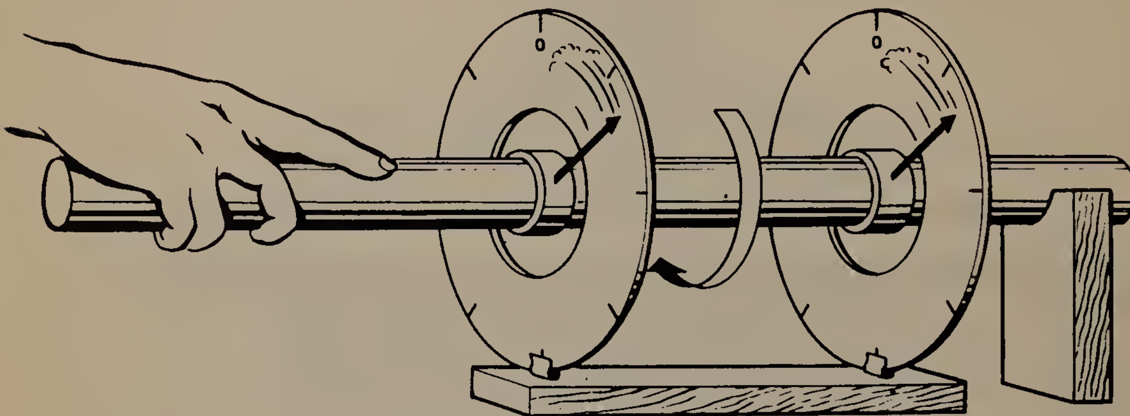
A simple synchro system can be very easily explained by considering it as an electrical equivalent of a long shaft of metal which transmits motion from one point to another.

When you turn one end of the shaft, the other end naturally turns in exactly the same manner; that is, at the same time, at the same speed and by exactly the same amount.

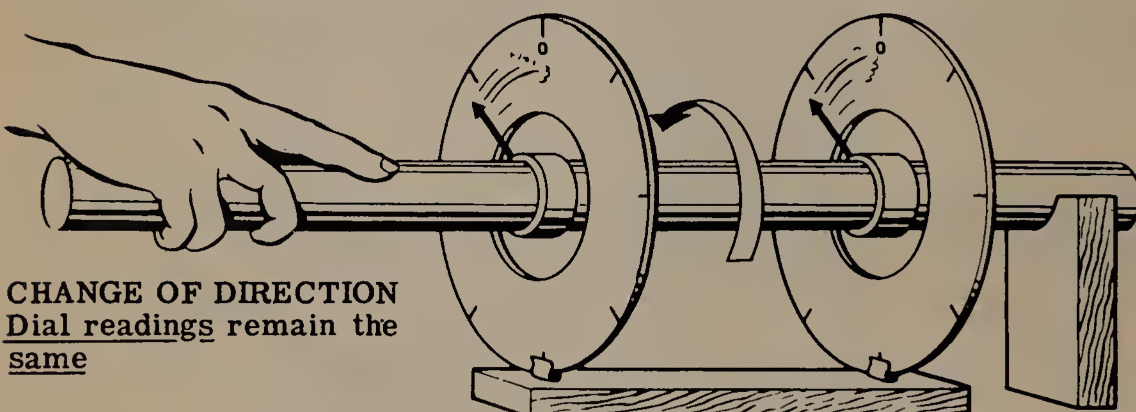


What a Synchro Is (continued)

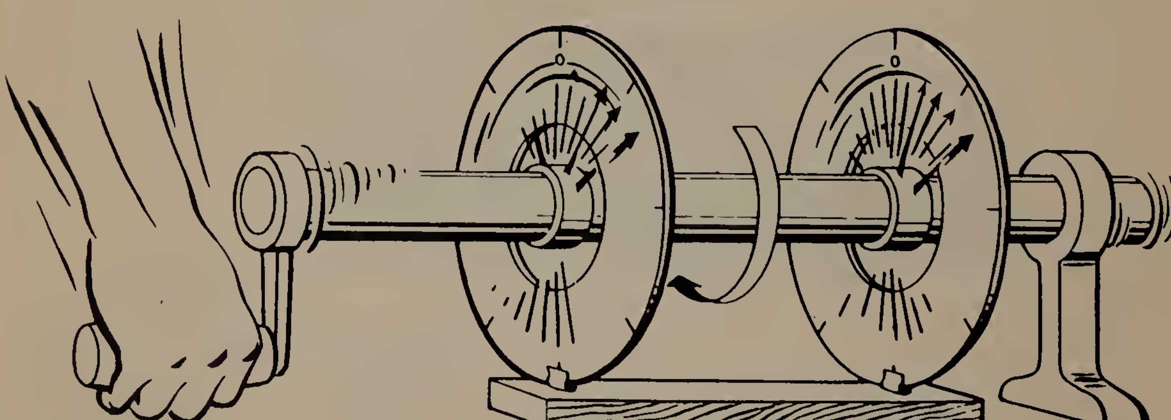
When you put a pointer and a dial at each end of the shaft, the dial readings will always be the same, provided they were the same when you began.



No matter in which direction you turn one end of the shaft, either fast or slow, the dial readings will always be the same.



CHANGE OF DIRECTION
Dial readings remain the same

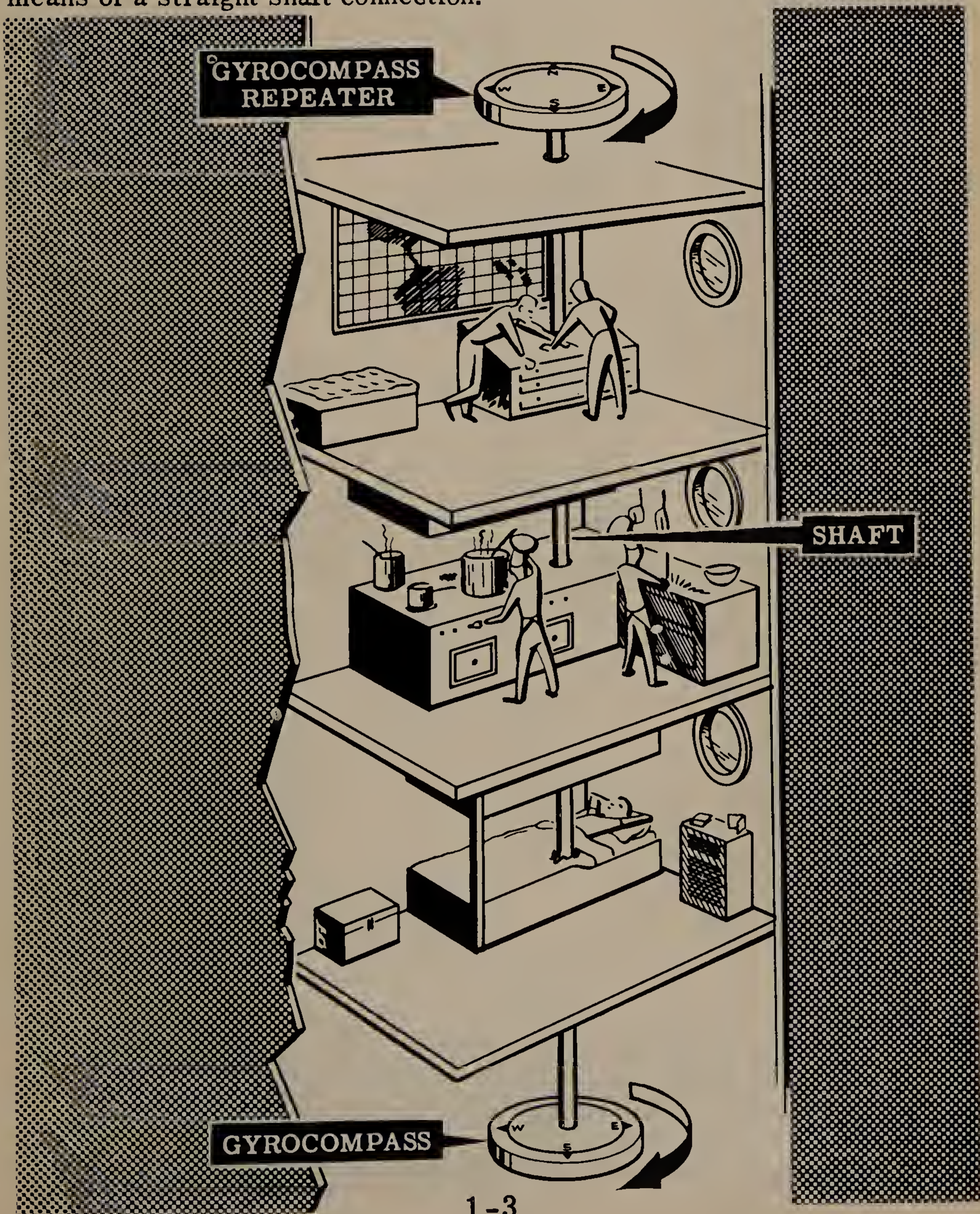


CHANGE OF SPEED
Dial readings remain the same

What a Synchro Is (continued)

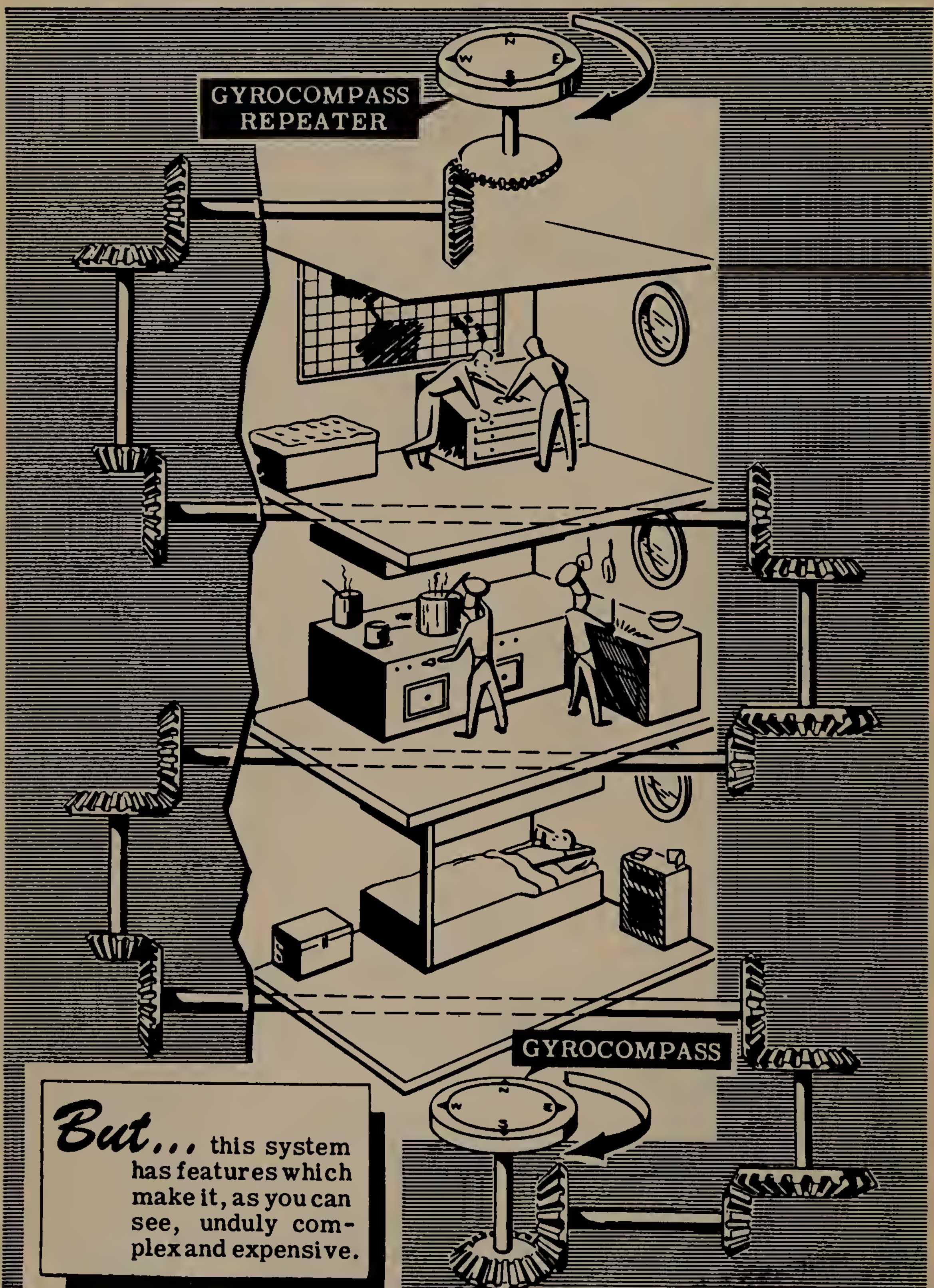
There is only one thing wrong with the solid shaft method of transmitting dial readings and doing work from a distance. The fault is that under many conditions, it would be very difficult to run a straight shaft between two points. Sooner or later something would get in the way, and that something might not like having a hole punched through it!

The illustration shows what would happen if a master gyrocompass aboard a ship were to transmit bearing readings to a gyrocompass repeater by means of a straight shaft connection.



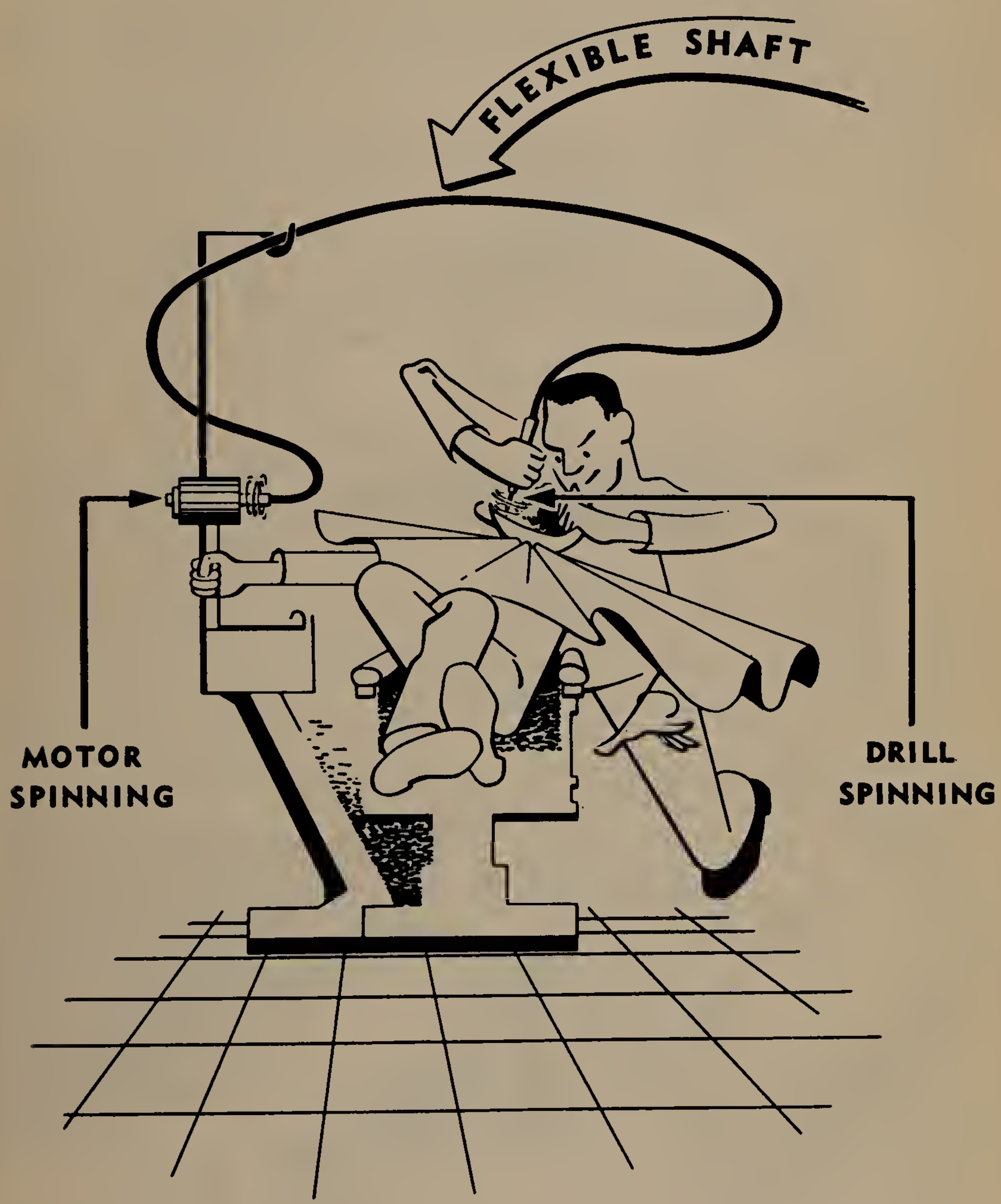
What a Synchro Is (continued)

The course of the shaft could be made to avoid obstructions by using a suitable system of gearing many small shafts together.



What a Synchro Is (continued)

The best mechanical solution would be to install a flexible shaft such as is used in automobiles to tune the radio, to transfer the turn of the wheels to the speedometer, etc.

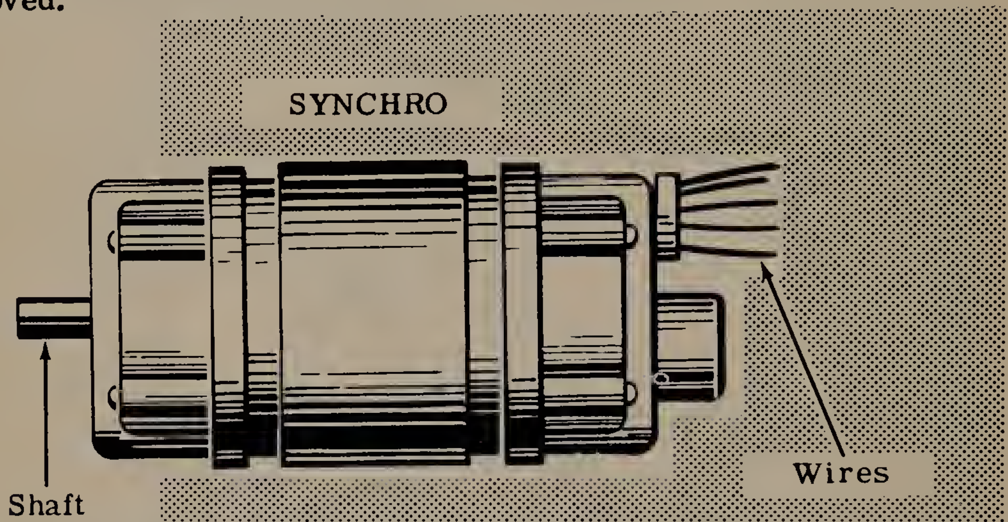


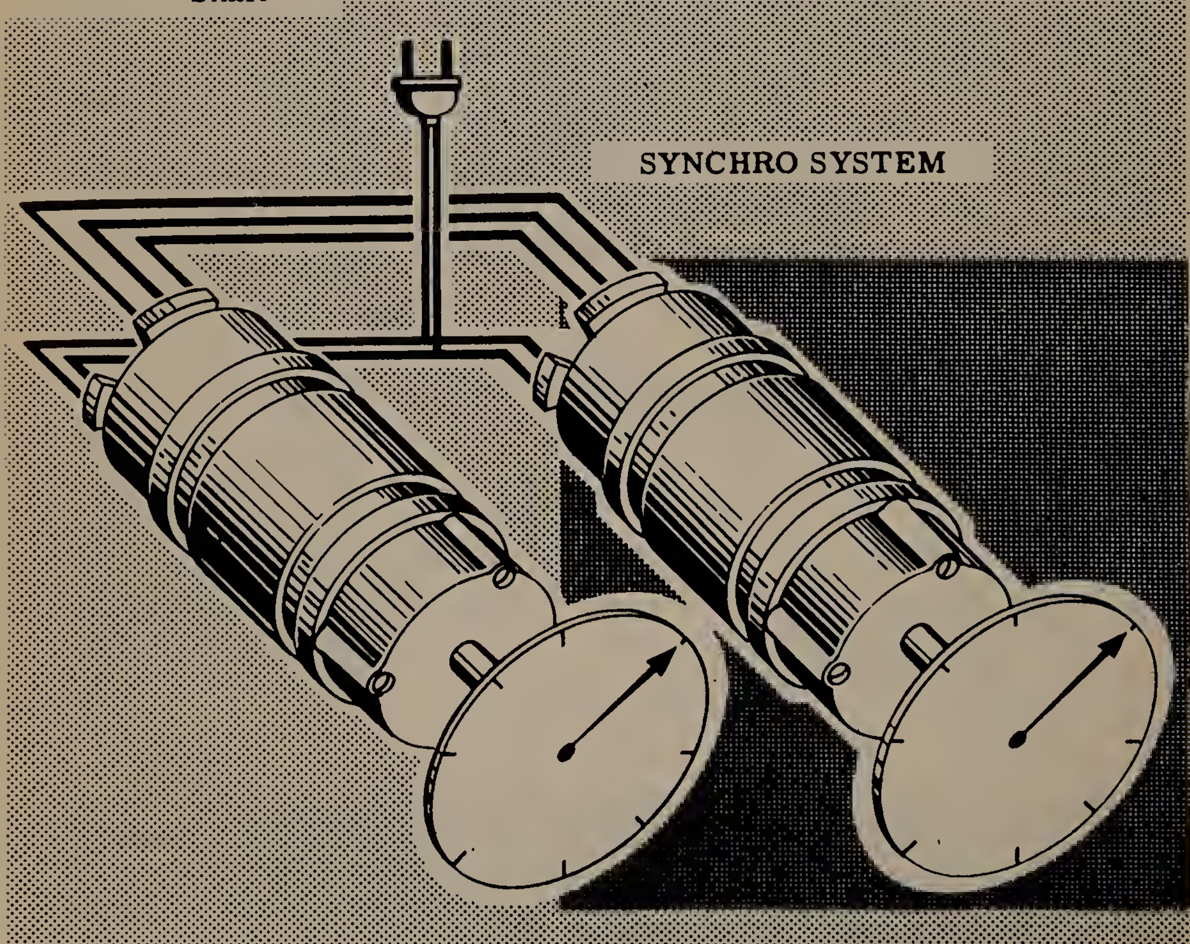
These flexible shafts, however, introduce a great deal of friction into the system. Besides, they can transmit only very tiny rotational forces. If an attempt is made to turn a moderately heavy load, the inside shaft begins to twist and the load does not follow the controlling force accurately enough for many uses.

What a Synchro Is (continued)

The simple answer to the problem of transmitting dial readings over a long distance, or turning a small load over a long distance, is the synchro.

A synchro is a gadget that looks like an electric motor, except that there are five wires coming out of it. When two synchros are connected together and to a source of AC voltage, they form a synchro system. This system acts like a flexible shaft in which all objectionable friction has been removed.





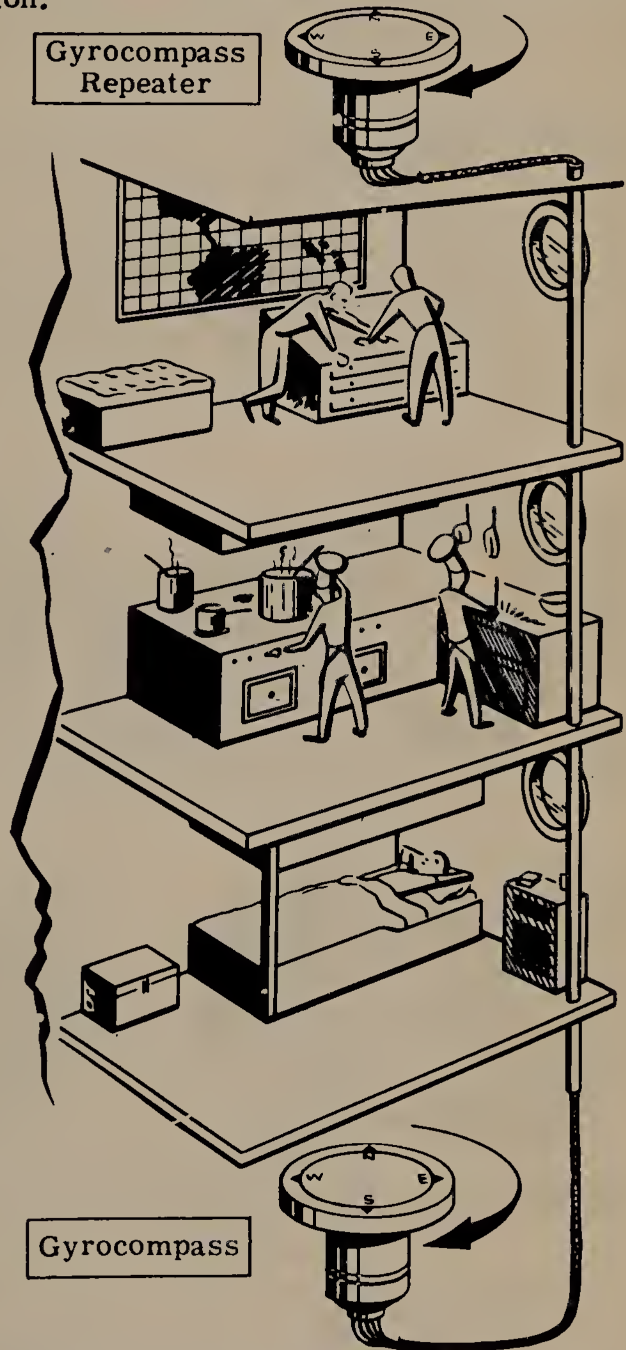
What a Synchro Is (continued)

When one synchro has its shaft turned, it transmits an electrical impulse over the wires. These electrical impulses turn the shaft of the other synchro to exactly the same position.

You can easily see how such a system can perform all the tasks of transmitting dial readings over a long distance.

A synchro system has these advantages over a mechanical connection:

1. The controlling shaft and the shaft that is controlled can be a long distance apart.
2. Any obstacle in the path can easily be bypassed by leading the connecting wires around it.
3. A synchro system uses very little electrical power and does away with the great complications of a purely mechanical connecting system.

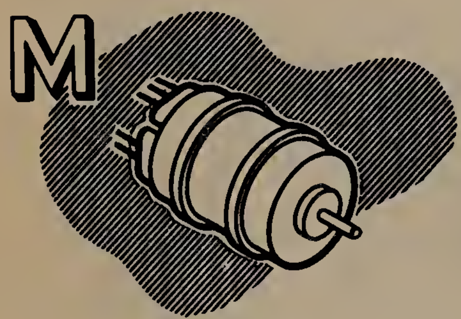


A simple synchro system can be used to turn light loads such as dials and pointers. If it is necessary to turn a heavy load, additional components must be added to the synchros. These components may be an amplifier to amplify the synchro signal and a motor to act upon the amplified signal and turn the load. The entire system is then called a "servomechanism." You will learn all about servomechanisms after you have learned about synchros.

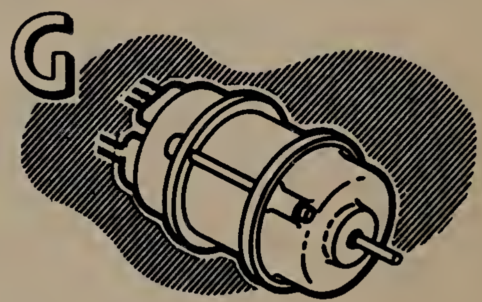
The Importance of Synchros

Some day you may have the responsibility of maintaining and servicing electronic equipment containing synchro systems. You should know exactly how synchros work so you will be able to service a defective synchro system successfully and thus help keep a vital piece of electronic equipment operating and doing its job.

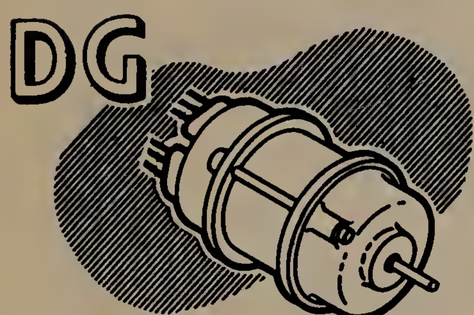
Before you begin to learn how synchros work, suppose you meet all the members of the synchro family—the synchro motor, the synchro generator, the synchro differential generator, the synchro differential motor and the synchro control transformer. These members of the synchro family have been around long enough for them to be known by more popular names. The synchro motor does not have any standard accepted name but it is often unofficially known as an "M." The others are known in the order previously mentioned as the "G," the "DG," the "D" and the "CT" and are so marked.



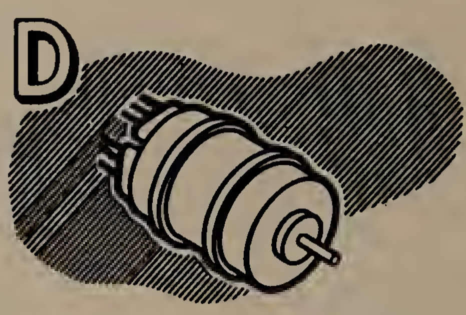
MOTOR



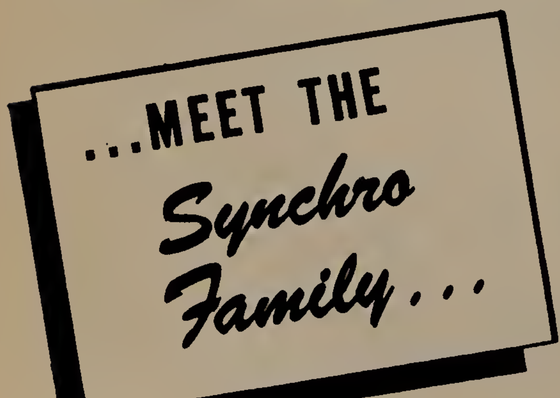
GENERATOR



DIFFERENTIAL GENERATOR



DIFFERENTIAL MOTOR

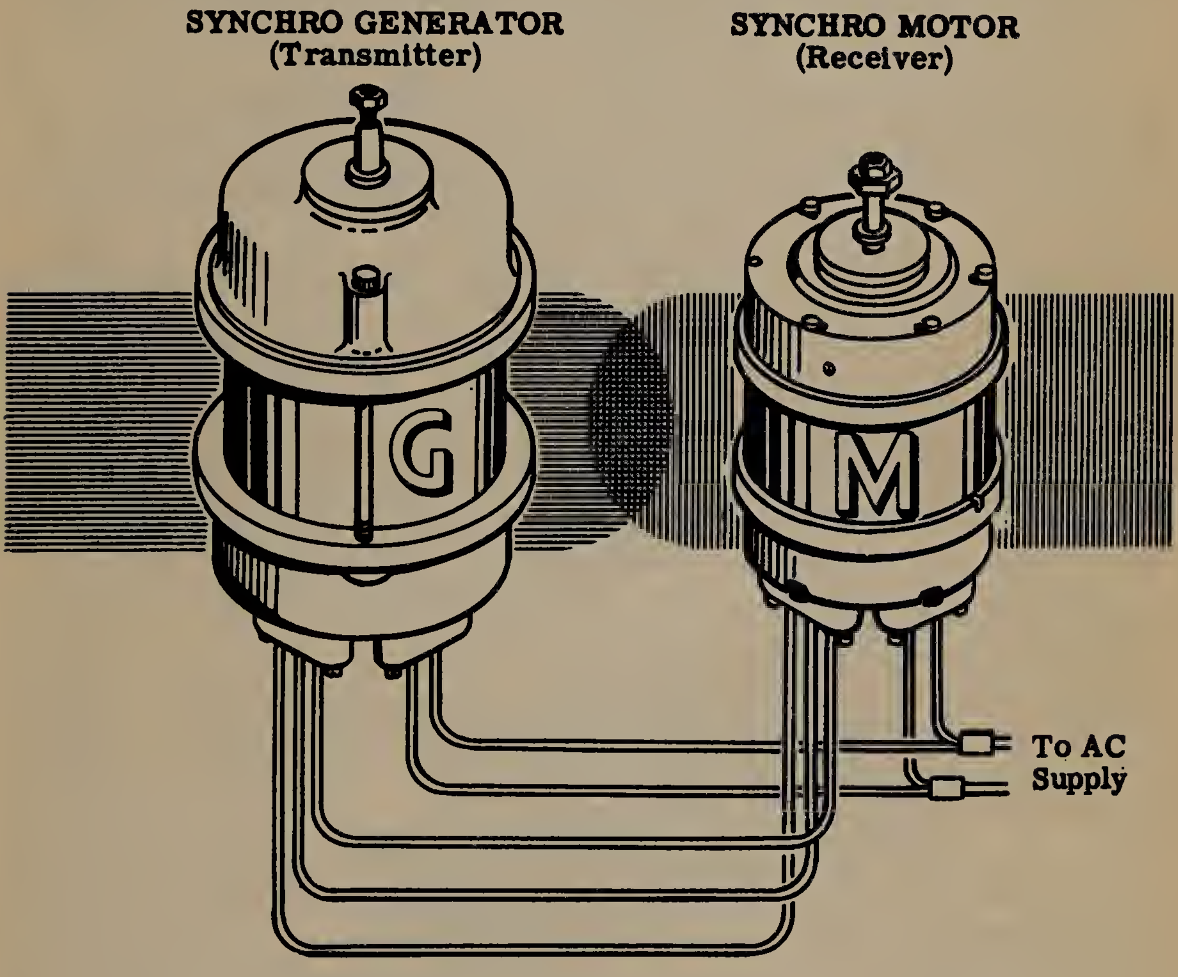


CONTROL TRANSFORMER

Synchro Generators and Motors

There are different types of synchros which are used in combinations to do various things. Combinations of synchros are called synchro systems.

The simplest synchro system is the team of a synchro generator (called a transmitter or a G) and a synchro motor (called a receiver or an M). In this system, when the shaft of the generator is turned, an electrical signal is generated and transmitted to the motor. This signal acts on the motor rotor, causing its shaft to rotate exactly the same number of degrees as the generator shaft.

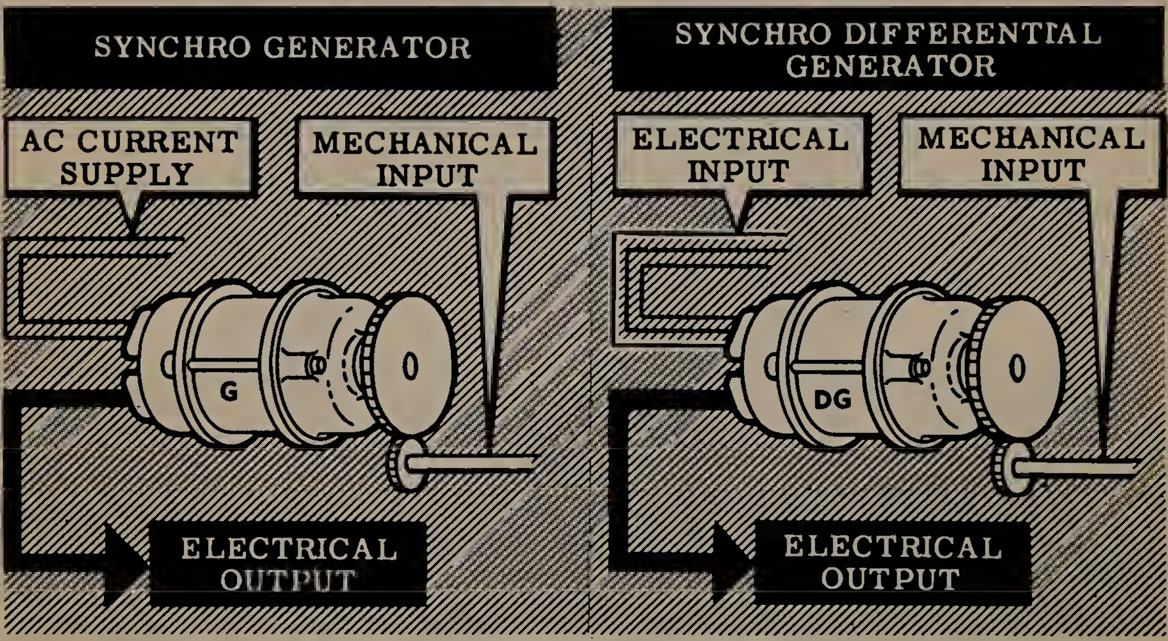


Here is a picture of such a system. You have already seen one of its applications, that of remotely determining "own ship's course" from the master gyrocompass. The generator-motor synchro systems also find extensive application in systems where they are actually a part of a complex servo system. The theory of operation of the generator-motor synchro system will be explained to you after you learn a little about the other types of synchro units used.

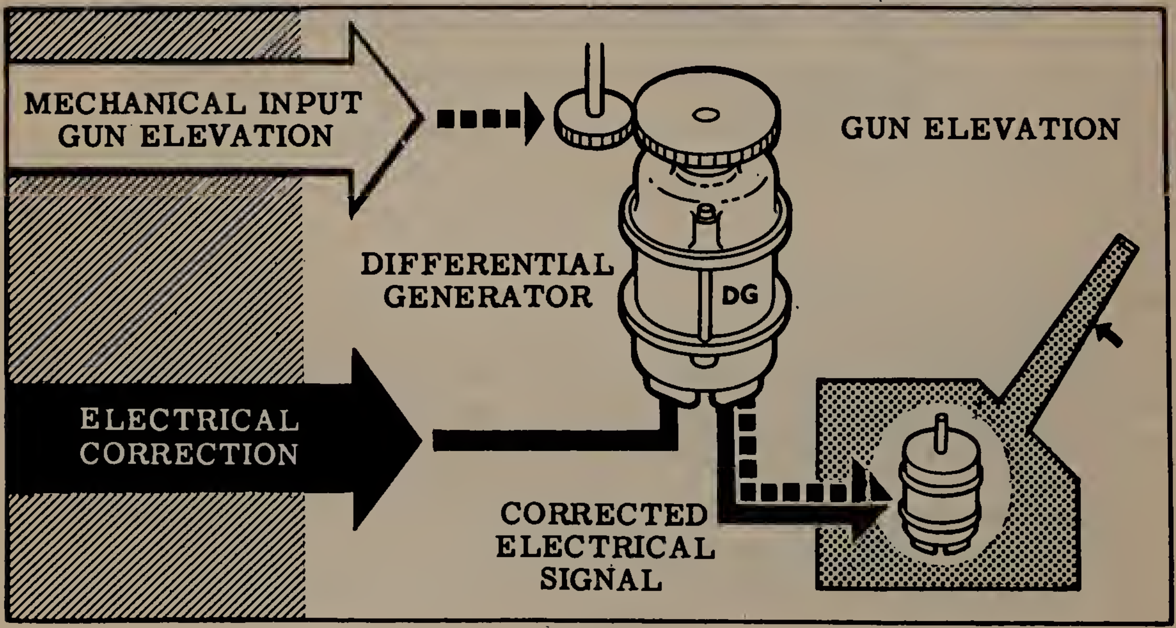
THE SYNCHRO DIFFERENTIAL GENERATOR

The synchro differential is another member of the synchro family that finds wide application in synchro systems. The synchro differential can be either a generator (transmitter or DG) or a motor (receiver or D).

The DG differs from the ordinary synchro generator in that it transmits the sum or difference of two signal inputs—one signal is usually fed in mechanically and the other signal is fed in electrically from another generator.

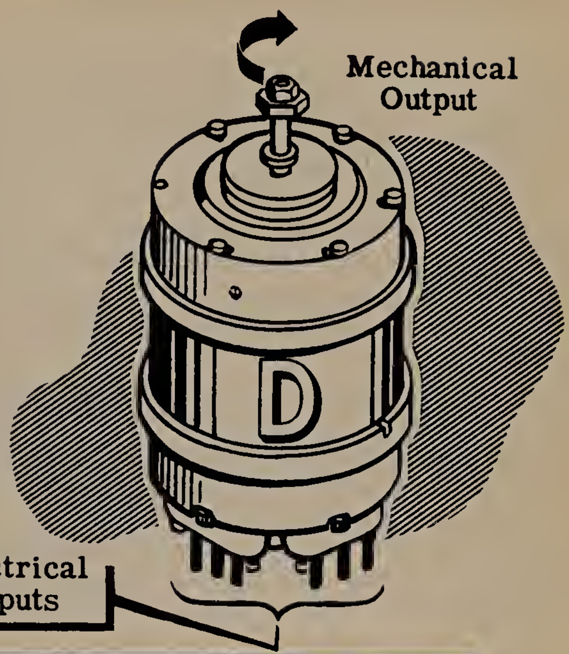


One military application of the synchro differential generator is found in fire control. For example, in one application the main gun elevation is mechanically cranked into a DG. If the gun elevation requires a correction, the correction signal is fed into the synchro differential generator electrically. The synchro/differential then gives to the gun the corrected elevation signal, which is the sum of the mechanical and electrical signals.



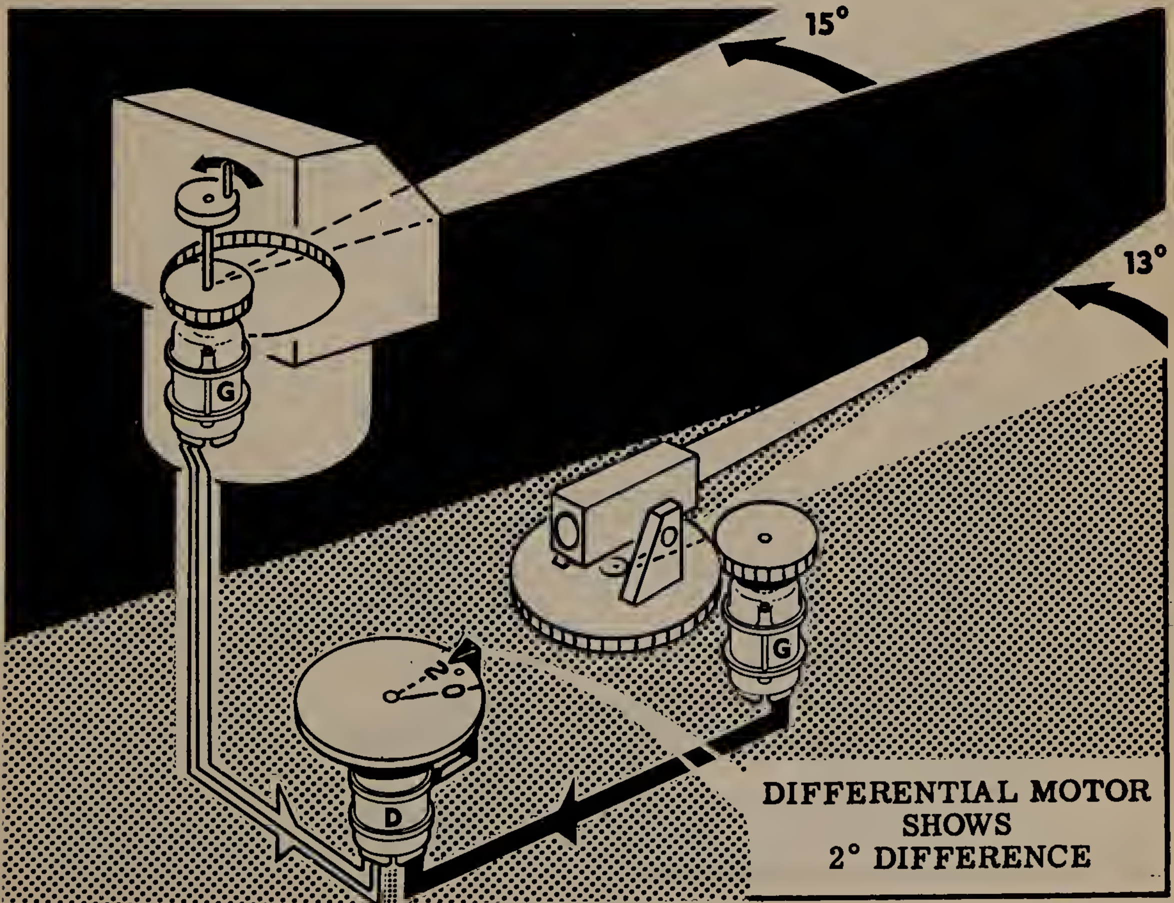
The Synchro Differential Motor

In the differential generator, a mechanical signal and an electrical signal are fed into the synchro and the output is an electrical signal which can either be the sum or difference of the input signals. In the differential motor (or D), the inputs are two electrical signals and the output is a signal transmitted mechanically by the shaft. The output signal can either be the sum or difference of the input signals.



TWO ELECTRICAL INPUTS—OUTPUT IS MECHANICAL

The differential motor, just like the differential generator, finds important applications in fire control. For example, the D may be used to indicate the difference in angular position between the director and the gun.



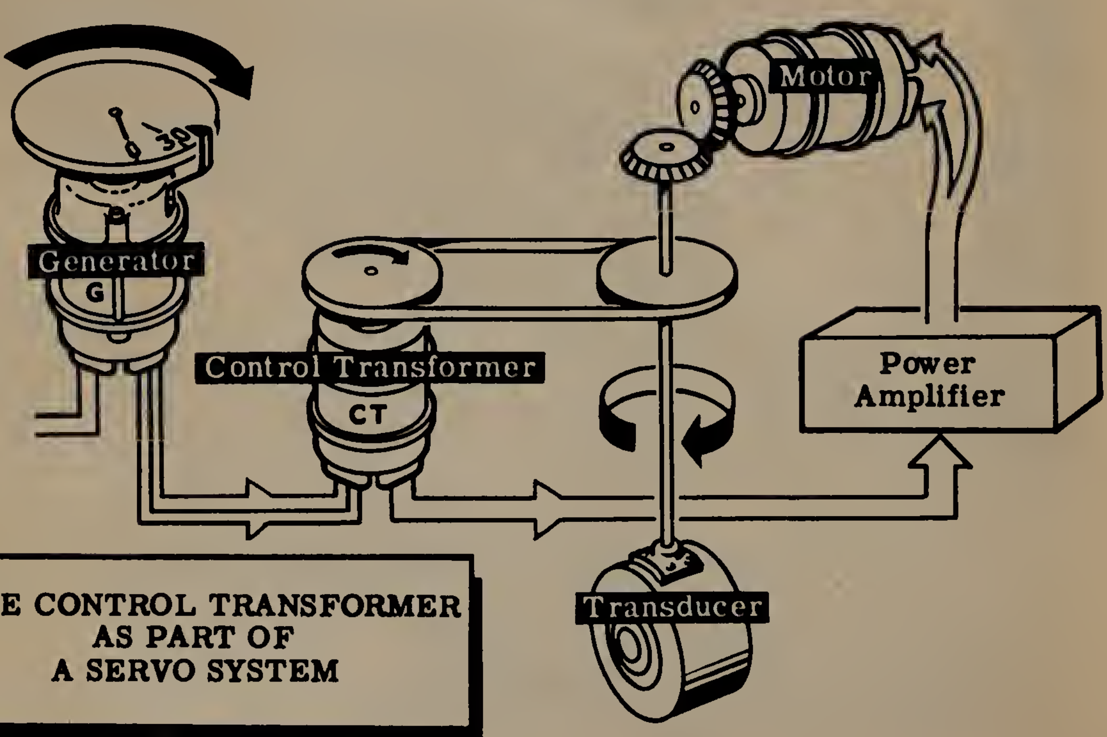
DIFFERENTIAL MOTOR SHOWS 2° DIFFERENCE

The Synchro Control Transformer

The synchro control transformer (CT) is the last member of the synchro family. Just like the others it finds wide application in synchro systems. The synchro control transformer is similar to the synchro motor in that it receives an electrical signal from either a synchro generator or a synchro differential generator. In a synchro motor the signal causes the rotor to turn one way or the other. In the CT, the signal produces a voltage output which varies in magnitude and in phase. This output voltage called an "error signal" is then applied as a signal to a power amplifier which drives a motor to position a mechanism.

The synchro control transformer, just like the other synchros, has some very important applications in remote control positioning systems. For example, the synchro control transformer may be part of a system whose function is to position the transducer of a sonar equipment. The illustration shows a generator sending a signal to a control transformer. The output from the CT is fed into a power amplifier which drives a motor. The motor turns the transducer and is also mechanically coupled to the rotor of the CT.

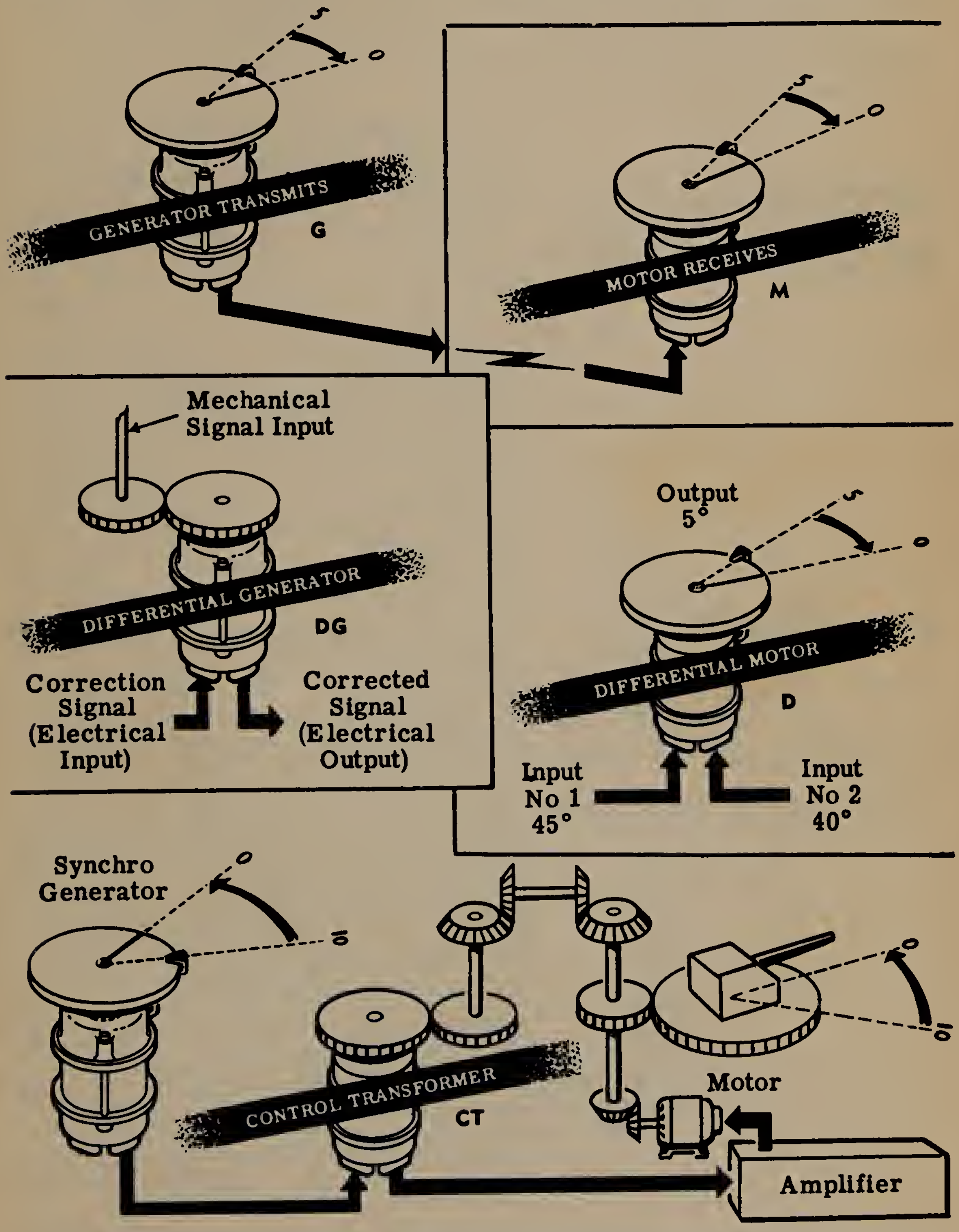
Very briefly here is the way the system works. When nothing is in motion, the system is in equilibrium and the output from the control transformer is zero. To turn the transducer 30 degrees clockwise, you turn the shaft of the G 30 degrees clockwise. The output voltage developed across the control transformer rotor is amplified so that it can turn the motor. The motor turns the transducer and, at the same time, turns the CT rotor in the same direction as the original signal turned the generator rotor. When the two rotors are lined up, the output from the rotor of the control transformer is zero and the motor stops turning. The transducer is now exactly 30 degrees clockwise from its original position.



THE CONTROL TRANSFORMER
AS PART OF
A SERVO SYSTEM

Synchro Systems

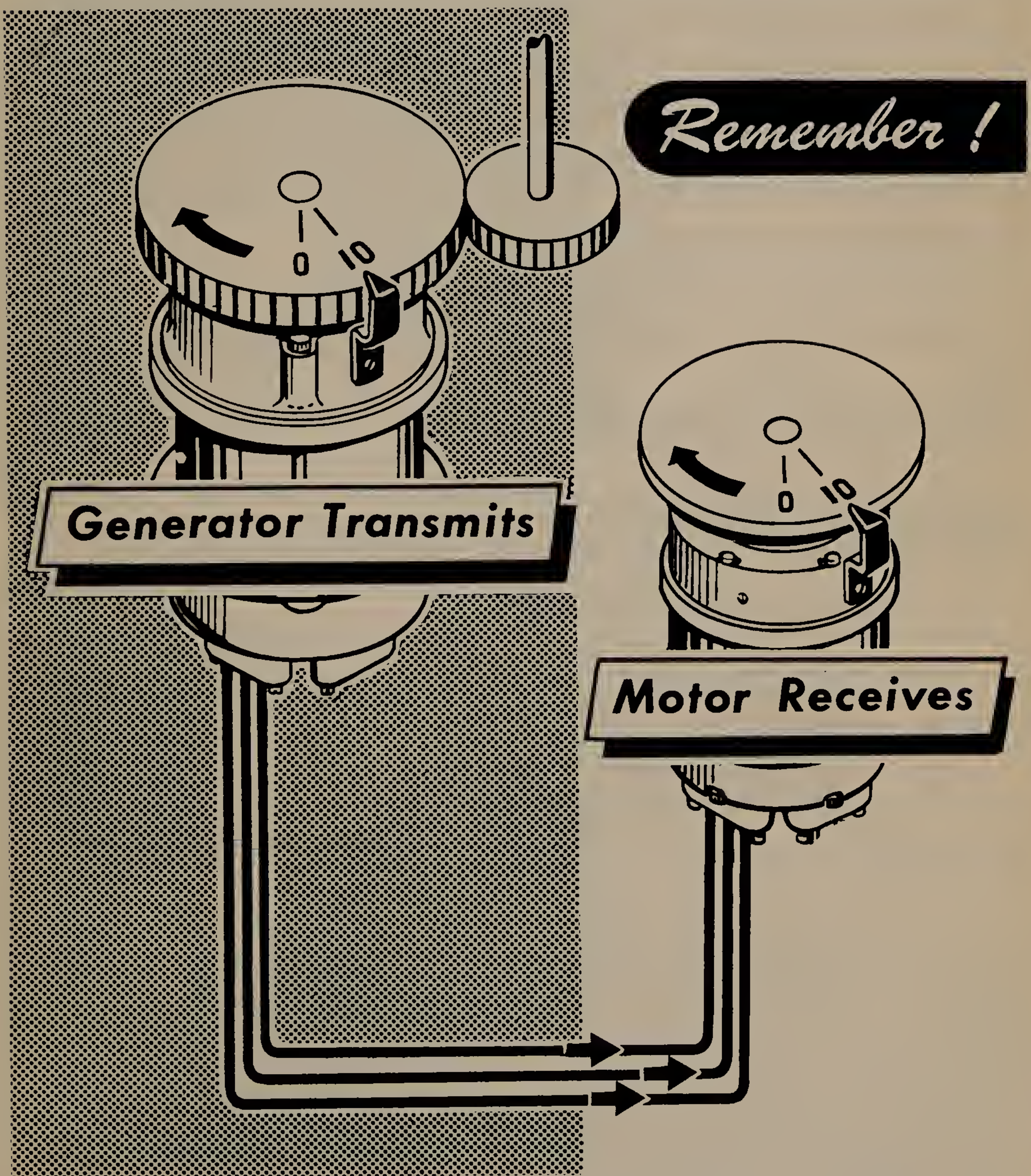
You have just been introduced to all the synchro components that make up synchro systems. You met the synchro motor, generator, differential and control transformer and you learned about some of their applications.



Now you are ready to go into the details of the operation of synchros and find out exactly how they work—both individually and in combination with each other.

General Information

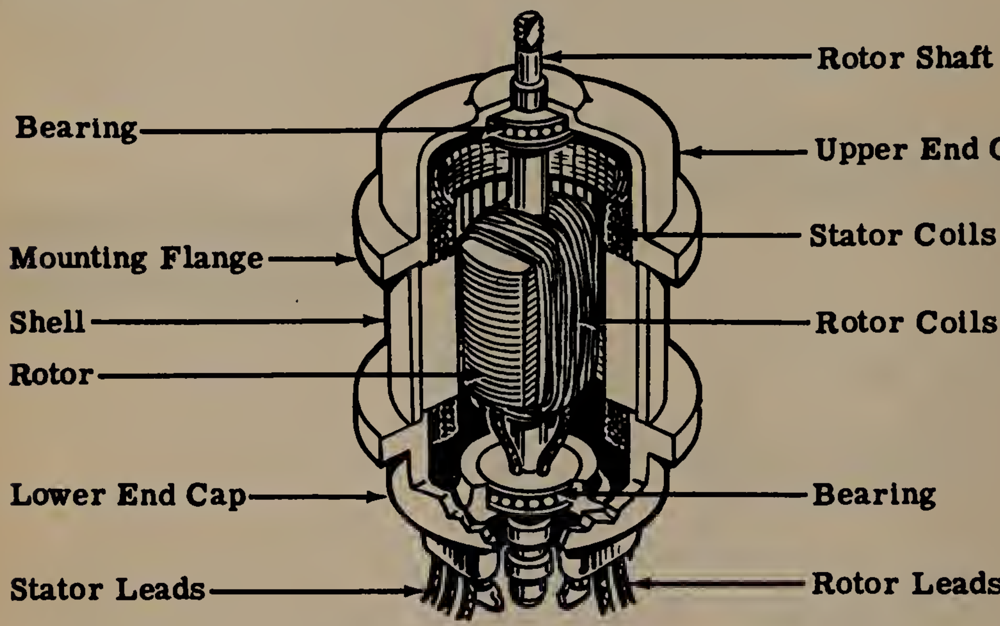
You already know that synchro generators and synchro motors are used to transmit information electrically from one point to another. You know that a signal is mechanically put into the generator by turning its shaft a certain number of degrees. The turning of the generator shaft is translated into an electrical signal which is then fed over wires to the motor. The electrical signal causes the shaft of the motor to turn at the same time and through the same number of degrees as the generator shaft.



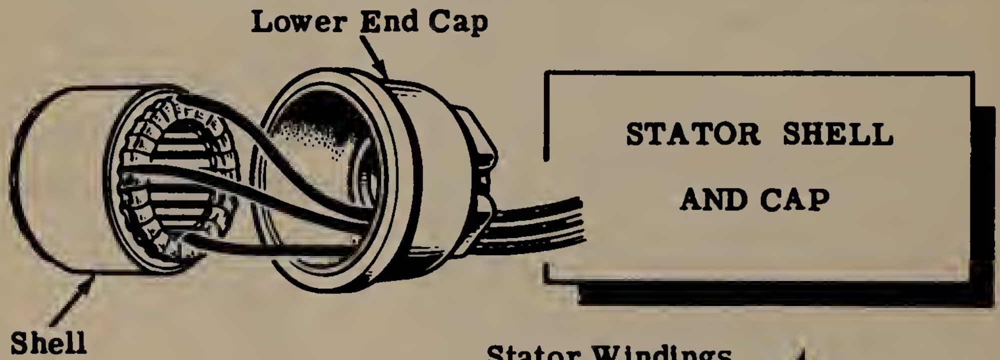
You also know that the turning of the motor shaft can be used to give a dial reading or it can be used to feed a mechanical signal into other complex mechanisms. Before you go into the theory of operation of the synchro generator-motor team, suppose you study their construction.

Synchro Generator Construction

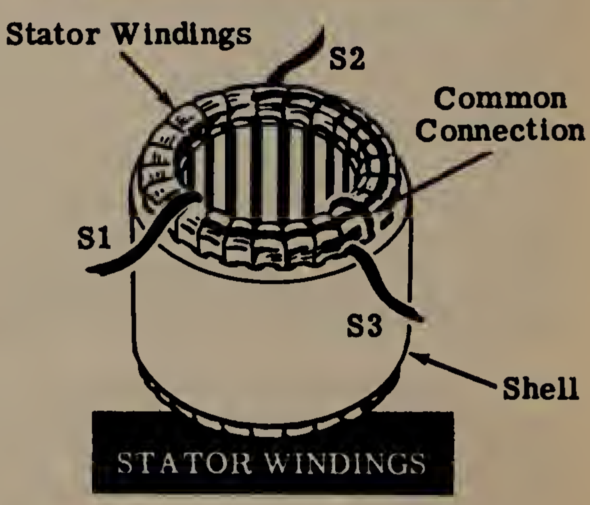
The illustration shows a picture of a typical synchro generator (or G) with a cutaway view revealing its internal construction. Observe that the internal construction looks very much like that of an ordinary motor or generator.



The G is made up of two major parts—the stator and the rotor. The stator consists of an upper end cap, a shell and a lower end cap. The inner surface of the shell is slotted, and these slots contain the stator winding.

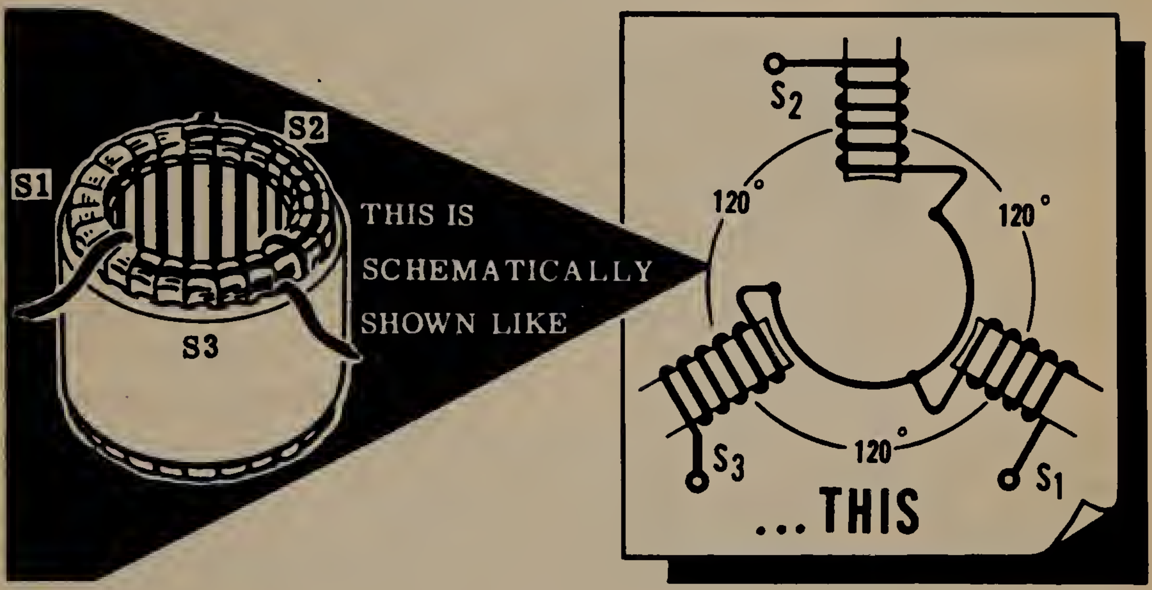


The stator winding is actually three separate windings spaced 120 degrees apart. Three leads, one from each of the three windings, are connected together to form a common connection inside the shell. The remaining three leads are brought out separately and are labeled S_1, S_2 and S_3. It is these three leads—S_1, S_2 and S_3—which transmit an electrical signal to the motor whenever the generator shaft is turned.

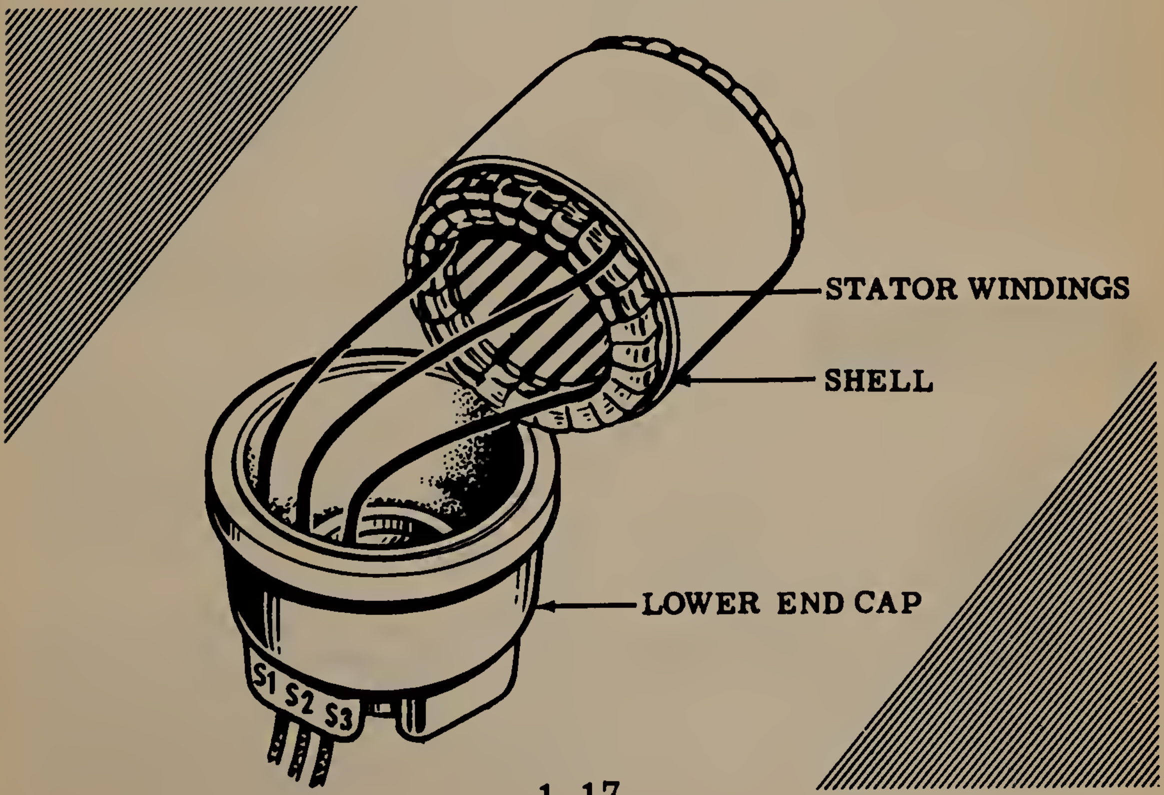


Synchro Generator Construction (continued)

The three windings are physically spaced 120 degrees apart. The way they are connected is called a star- or Y-connection. The diagram shows the schematic symbol for representing the stator windings.



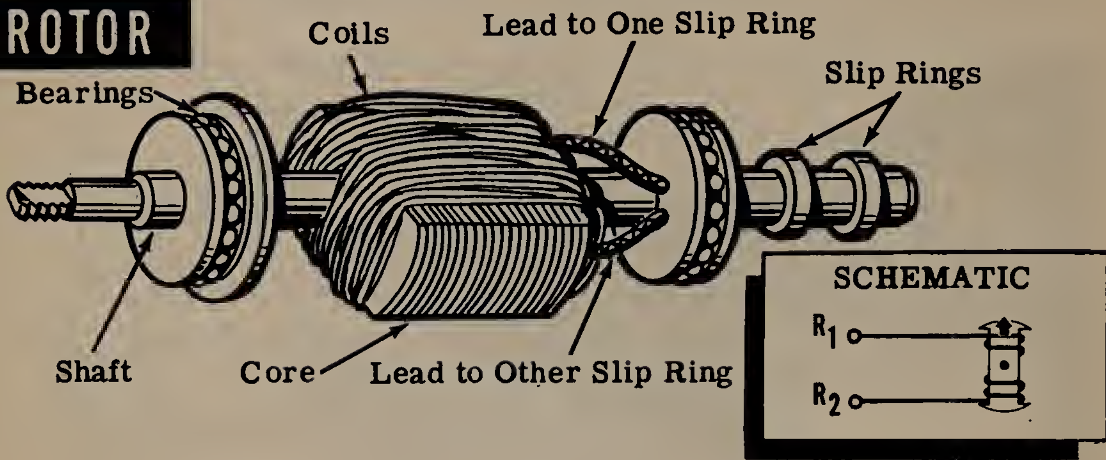
The illustration below shows how the shell and its stator windings fit into the lower end cap. Notice that the three stator leads S_1, S_2 and S_3 pass through the lower cap and come out into the open.



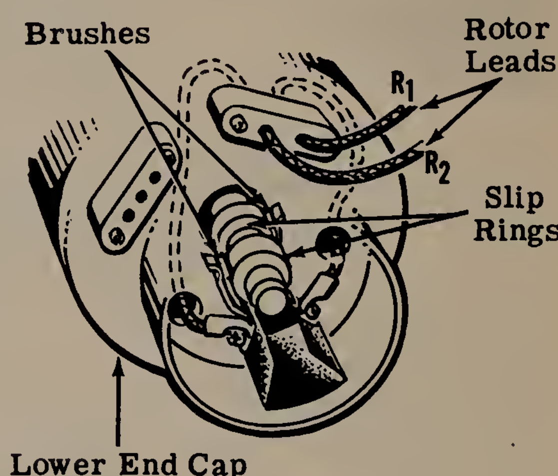
Synchro Generator Construction (continued)

The rotor of the G is shown in the illustration. The schematic symbol representation for the rotor is also shown.

ROTOR

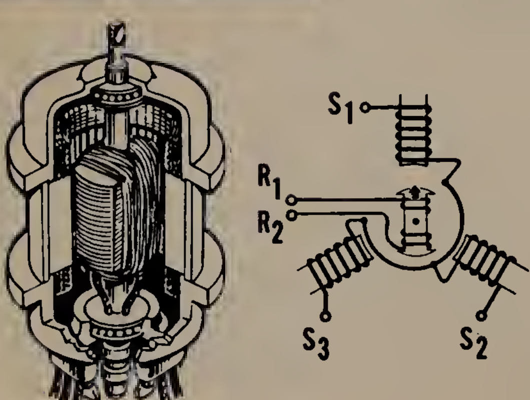


The rotor is made up of two coils which are connected in series to form one continuous winding. These coils are wound on a laminated, bobbin-shaped, iron core to form the complete rotor assembly. The ends of the rotor assembly are mounted in ball bearings to permit frictionless rotation of the shaft. The ends of the rotor windings connect to two slip rings on the rotor shaft. The slip rings bear against two metal brushes which are assembled inside the lower cap and to these are connected leads labeled R_1 and R_2 as illustrated.



ROTOR LEADS ARE CONNECTED TO BRUSHES

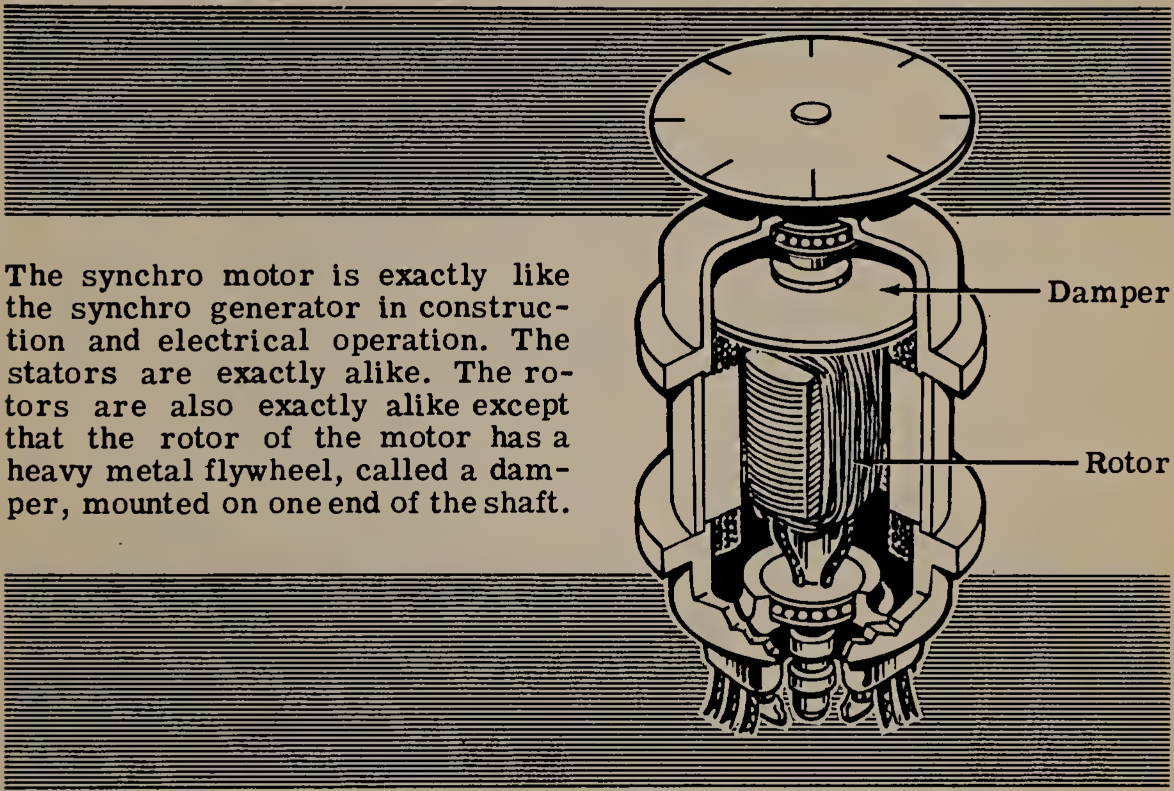
GENERATOR



When the rotor is assembled inside the shell housing, it is free to turn whenever current is supplied to the rotor winding through leads R_1 and R_2.

The complete generator and its schematic representation are shown—at the left. Now that you know how the synchro generator is constructed, suppose you find out about the construction of the synchro motor.

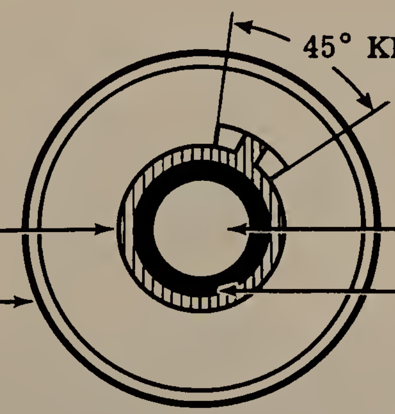
Synchro Motor Construction



The synchro motor is exactly like the synchro generator in construction and electrical operation. The stators are exactly alike. The rotors are also exactly alike except that the rotor of the motor has a heavy metal flywheel, called a damper, mounted on one end of the shaft.

The purpose of the damper is to prevent the shaft of the motor from oscillating or spinning at a high speed. Without this flywheel, this would happen when the shaft was turned quite suddenly or when the power was first turned on.

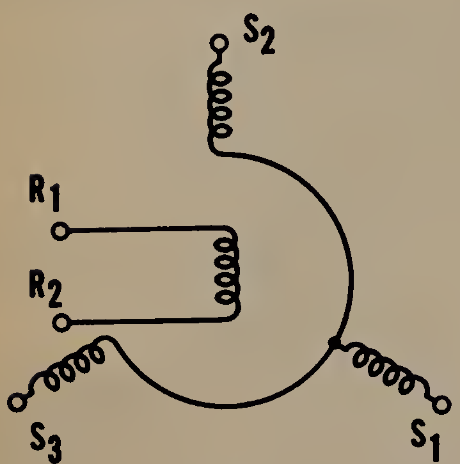
The flywheel is mounted so that it turns freely on the shaft for 45 degrees and then runs into a keyed bushing. This bushing is fastened to the shaft through a friction disc so that it can turn on the shaft only with a great deal of friction.



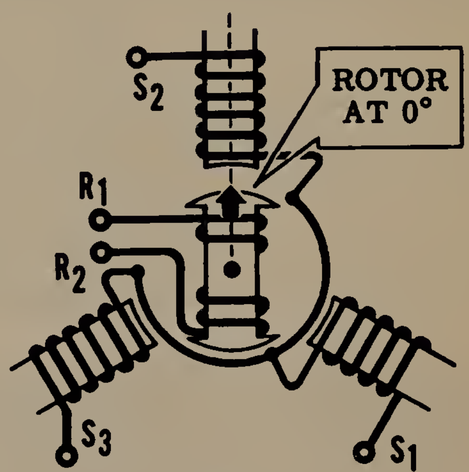
When the shaft rotates slowly, the flywheel simply follows along and does not move relative to the shaft. However, when the shaft turns suddenly, the flywheel tends to stand still due to its inertia. The keyed bushing, hitting up against the flywheel, is stopped, and the friction disc acts as a brake on the shaft, slowing it down. Thus the shaft never gets going fast enough to start oscillating or spinning.

Synchro Schematics

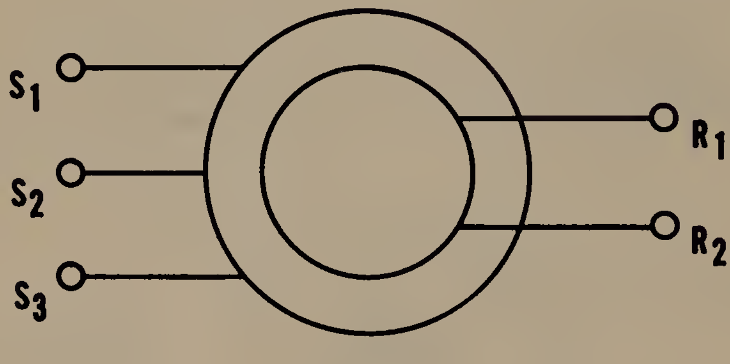
Generator and motor synchros are represented by the same schematic symbol, which may be drawn in three different ways.



A



B



C

Schematic A is the one that is most commonly shown. Schematic B is often drawn when an explanation is given of the operation of a synchro. Schematic C is a very simple way of drawing the symbol.

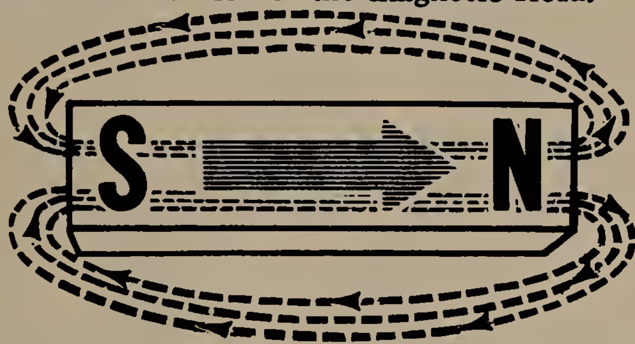
A synchro generator or motor is said to be positioned at zero degrees when the axis of the rotor lines up with the axis of the S_2 winding. This is clearly shown in Schematic B.

Now that you know how synchro motors and generators are constructed, you are ready to find out how they work.

Magnetic Fields

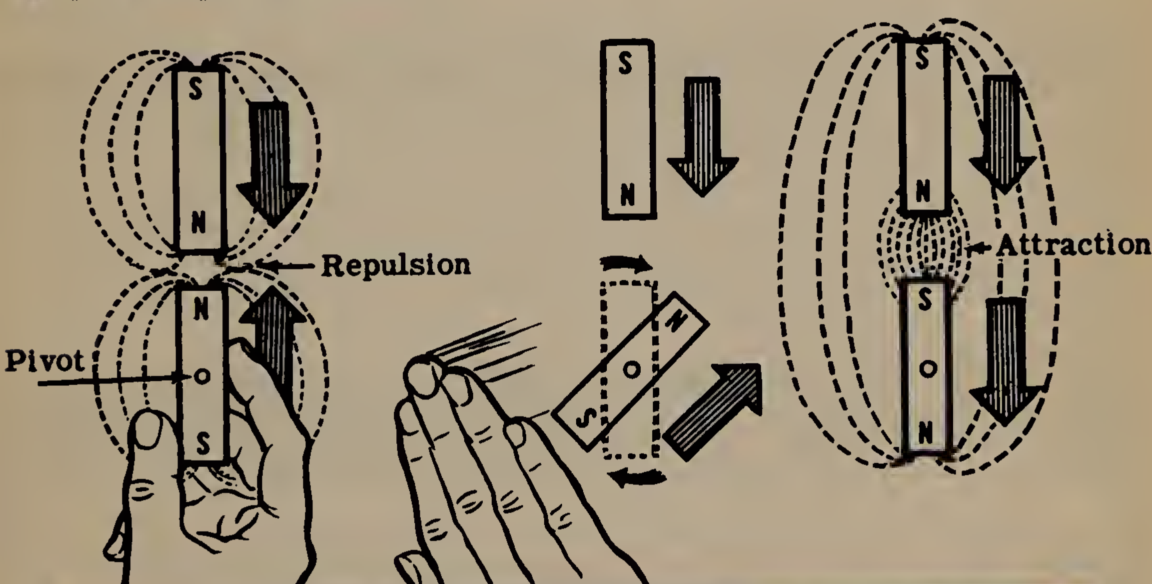
In order to help you understand how synchros work, you are first going to review some theory on magnets and magnetic fields.

Suppose you take a look at a bar magnet and observe the relationship between its poles and the direction of the magnetic field.



Notice that the magnetic lines of force flow from the south pole to the north pole inside the magnet. The direction of the magnetic field can therefore be represented by an arrow pointing in the direction of the north pole as indicated.

Now consider two bar magnets, one of which is permanently fastened in place and the other being free to rotate about a center pivot. If the free bar magnet is rotated by hand until its north pole end is facing the north pole end of the fixed magnet, a strong force of repulsion is set up since like poles repel each other.

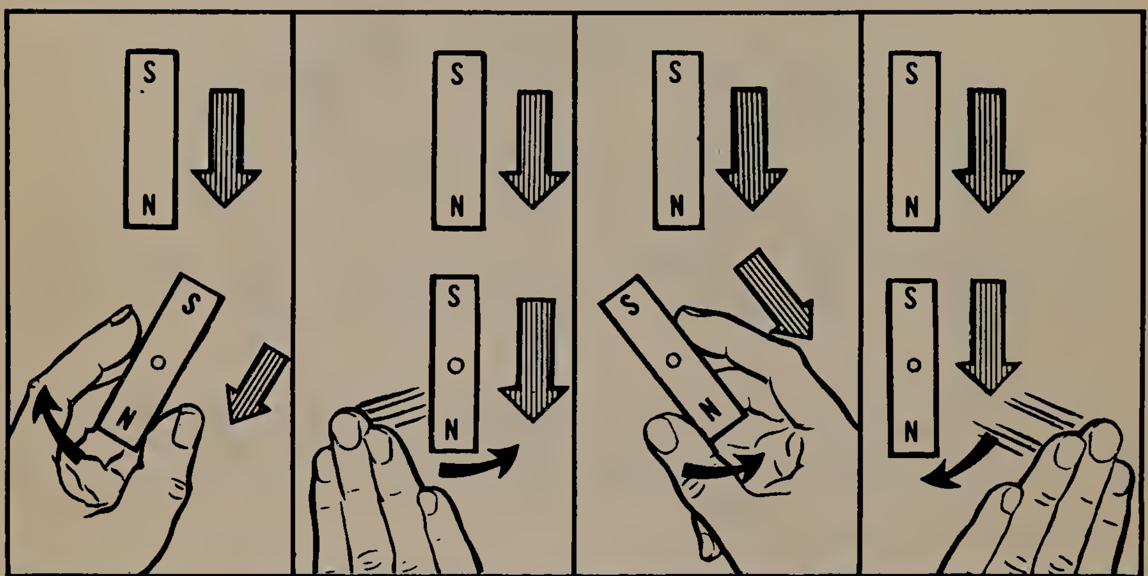


REPULSION AND ATTRACTION

Observe that the arrows representing the direction of the magnetic fields point in opposite directions. If the pivoted magnet is suddenly released, it will immediately rotate through 180 degrees until its south pole is facing the opposite north pole. Notice now that the arrows point in the same direction.

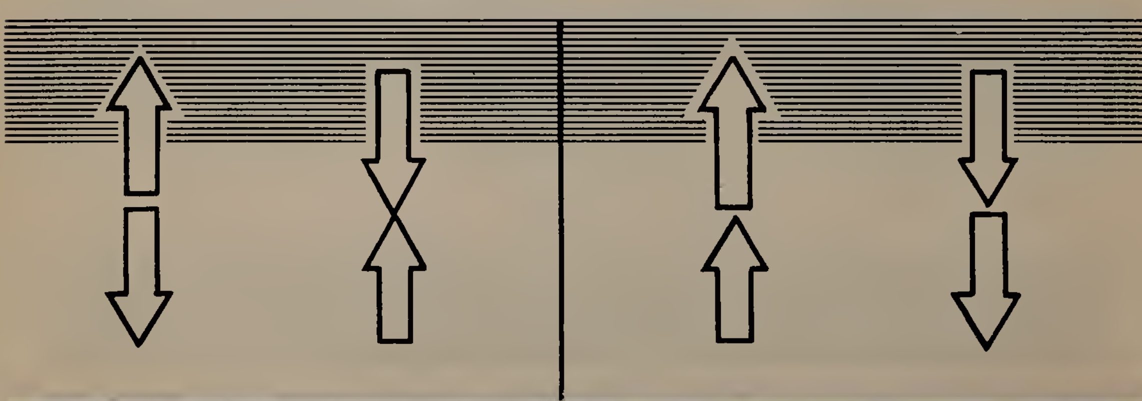
Magnetic Fields (continued)

Suppose you turn the pivoted bar magnet away from its equilibrium position, the position where it is lined up with the other magnet. Turning the magnet just a little bit will immediately move the north and south poles and the magnetic field arrows away from each other. A force of attraction is set up which will attempt to return the bar magnet to its original position where the arrows are in line. If you turn the magnet in the opposite direction, a similar force of attraction will be set up which will again try to return the bar to its equilibrium position.



MAGNETIC FIELDS TRY TO LINE UP IN ATTRACTION

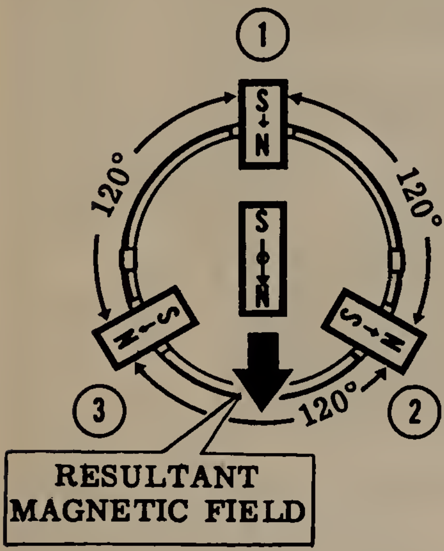
What have you learned by reading about this simple experiment with two magnets? You learned that when two magnetic field arrows are shown pointing in opposite directions, it means that the fields are in opposition and a strong force of repulsion exists between the two fields. If, however, two magnetic field arrows are shown pointing in the same direction, it means that the fields are aiding each other and a strong force of attraction exists between the two fields.

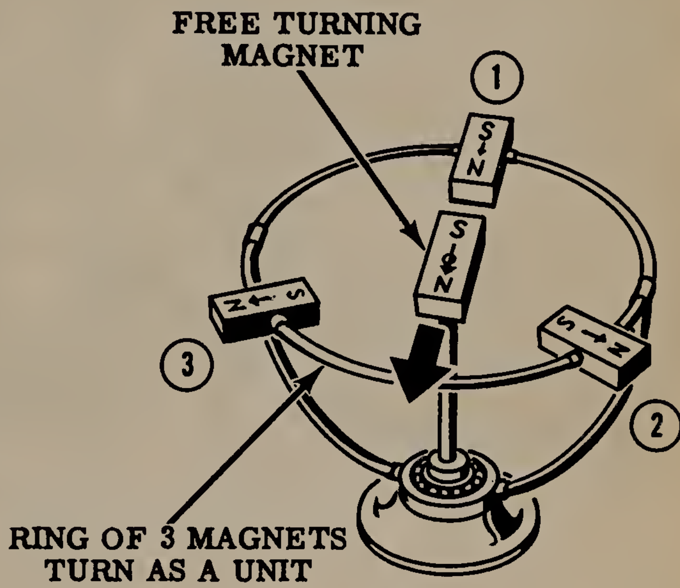


this means REPULSION | *this means* ATTRACTION

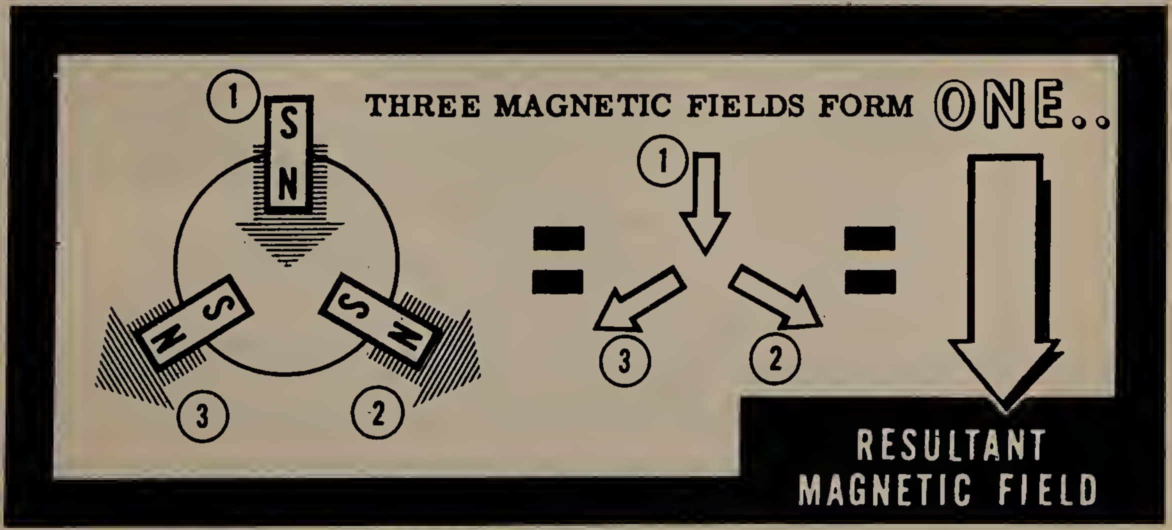
Magnetic Fields (continued)

You will now try another experiment using three equal magnets spaced 120 degrees apart, the entire set being mounted so as to be free to turn as one unit. In between the magnets is placed another magnet which is free to turn about a pivot at its center.



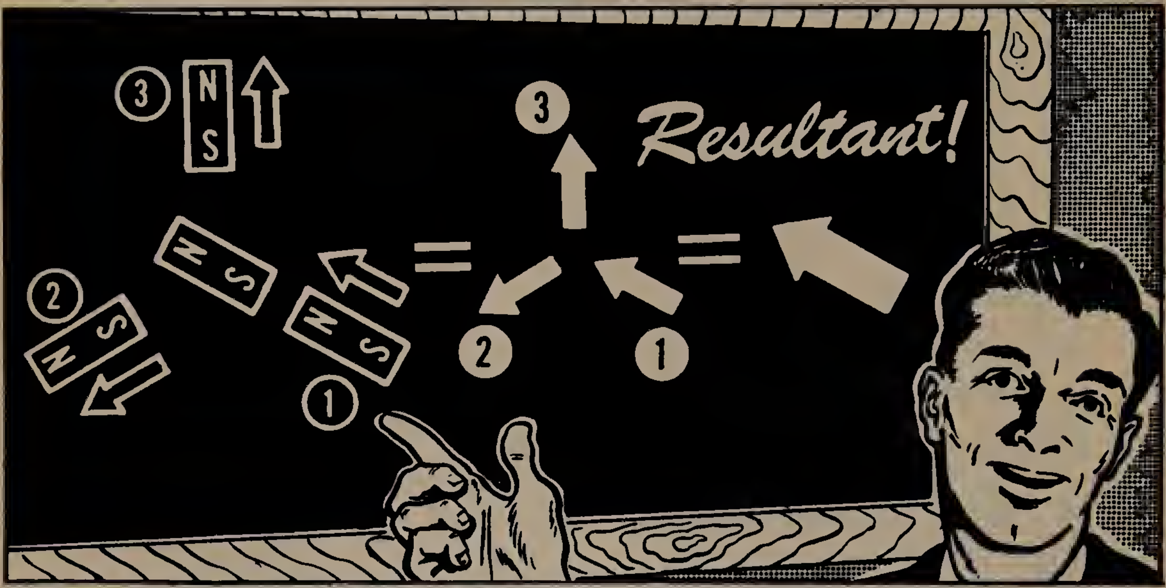


If the ring of three magnets is held, the single pivoted magnet will move so that its south pole is in line with the north pole of magnet number 1. Since its north pole is attracted equally by the south poles of magnets 2 and 3, it will remain between the two. The pivoted magnet therefore lines up with magnet number 1. How have the individual magnetic fields of the three magnets acted upon the pivoted magnet? The three magnetic fields have acted together as if they were one magnetic field which is pointed in the same direction as magnet number 1. In other words, the three magnetic fields combine to form one resultant magnetic field as shown.

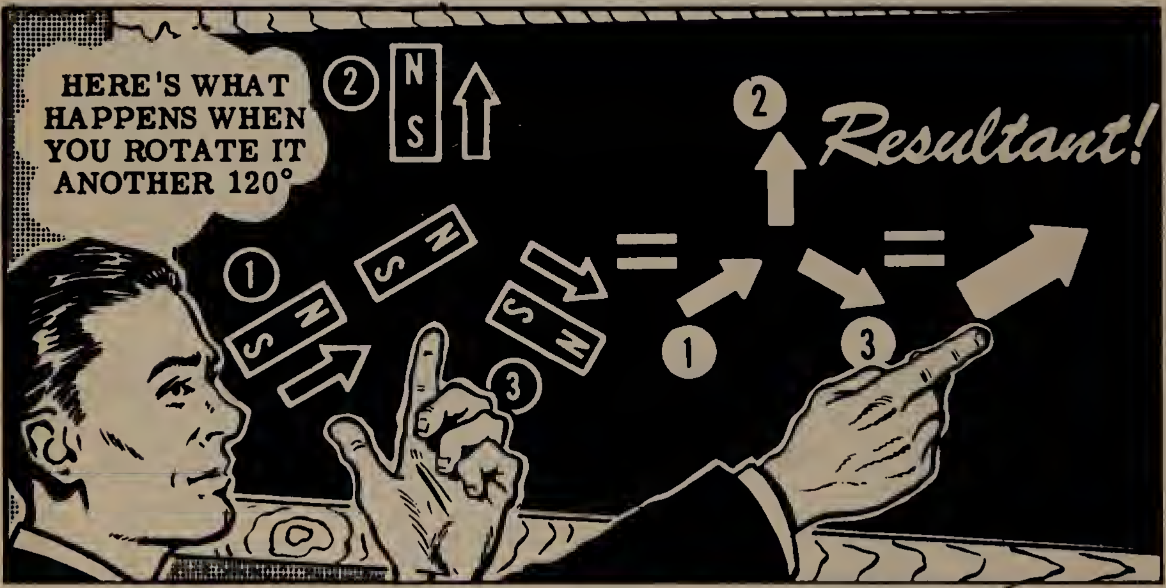


Magnetic Fields (continued)

If the three magnets are now rotated 120 degrees and then held in that position, the resultant magnetic field is also rotated through 120 degrees. The pivoted bar magnet will turn in the same direction so as to remain lined up with the resultant magnetic field of the three magnets.



Rotating the three magnets as a unit through another 120 degrees will again cause the resultant magnetic field to rotate through another 120 degrees. Again the bar magnet will follow the resultant magnetic field and line up with it.

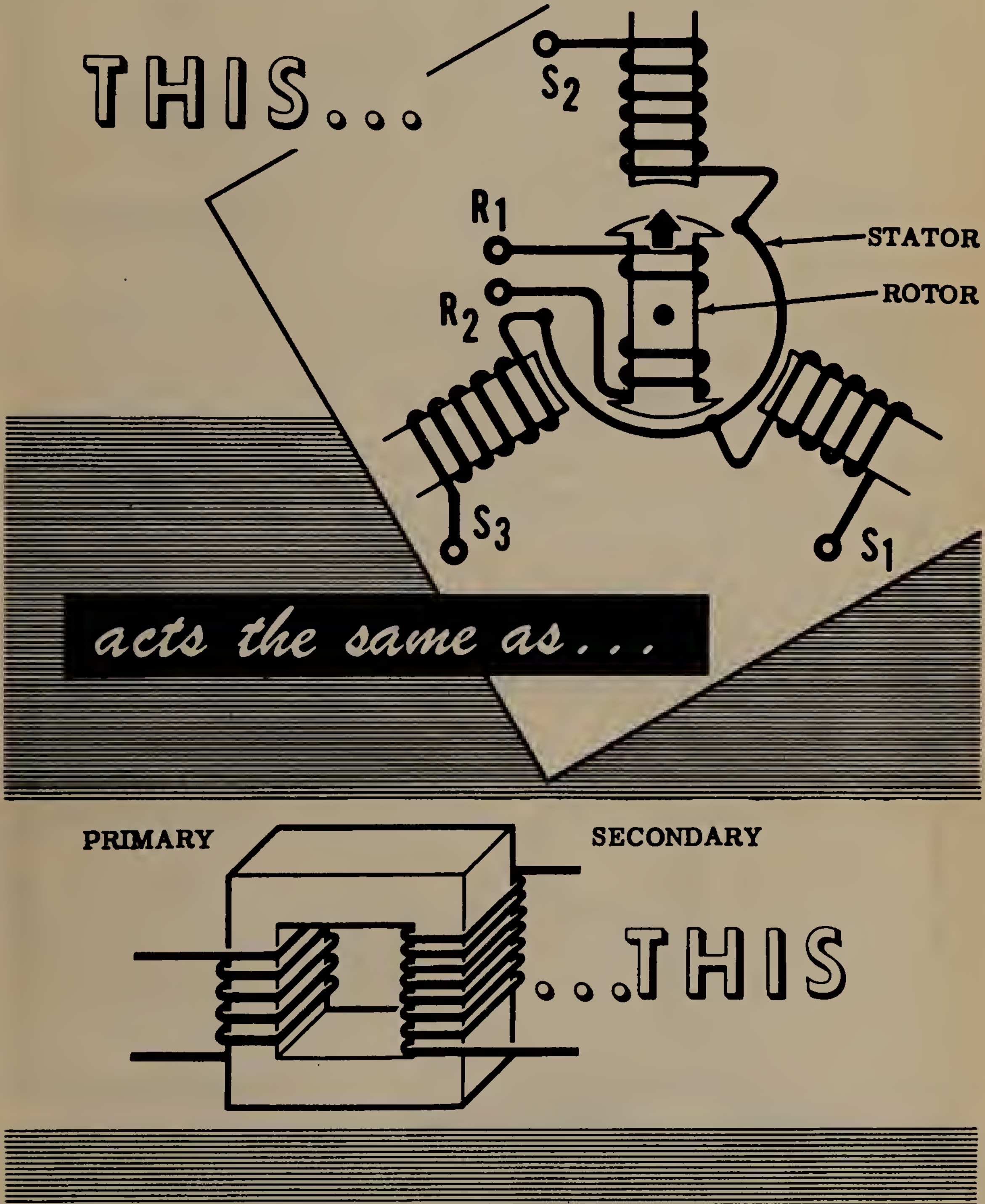


These simple experiments have indicated to you that three magnetic fields spaced 120 degrees apart can combine together to produce one resultant magnetic field. For all practical purposes you can forget about the three individual fields and only consider the resultant magnetic field as influencing the position of the pivoted bar magnet.

The next step in learning about synchros is to see how they act like transformers.

Simple Transformer Theory

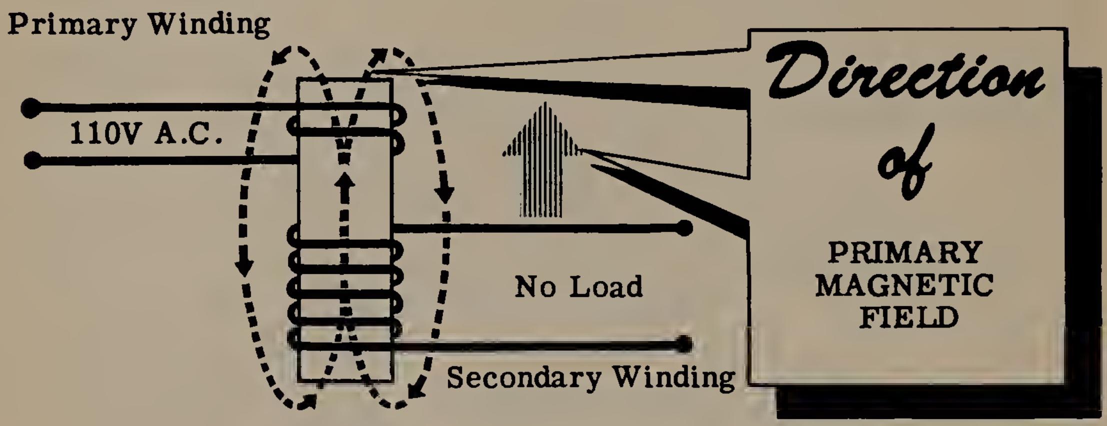
If 110 volts AC are applied to the rotor of a synchro generator, an alternating magnetic field will build up about the rotor winding. This alternating magnetic field will cut through the turns of the three stator windings and by transformer action induce a voltage in them. The rotor and stator windings of a synchro act just like the primary and secondary of an ordinary transformer.



Suppose you review some fundamentals of transformer action to help you understand how synchros work.

Simple Transformer Theory (continued)

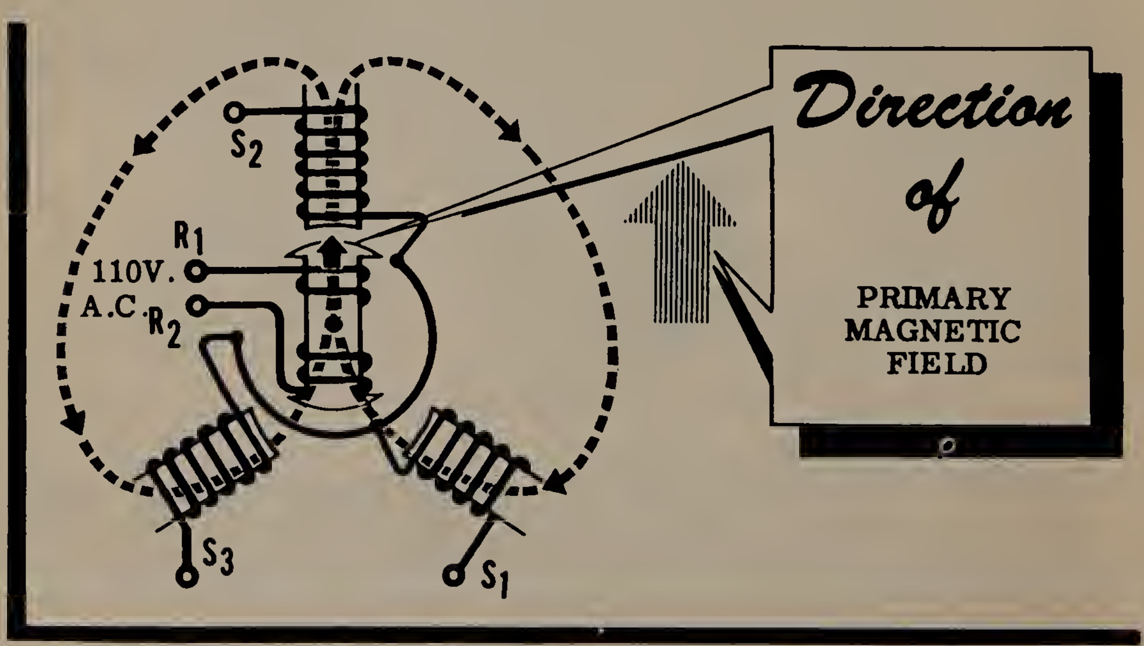
Suppose you consider the operation of a simple transformer.



When an AC voltage is applied to the primary winding, a magnetic field will build up about the primary. Let us assume that when the AC voltage is in its positive alternation, the direction of the magnetic field is up as shown. We can represent this upward direction of the magnetic field by an arrow facing upward.

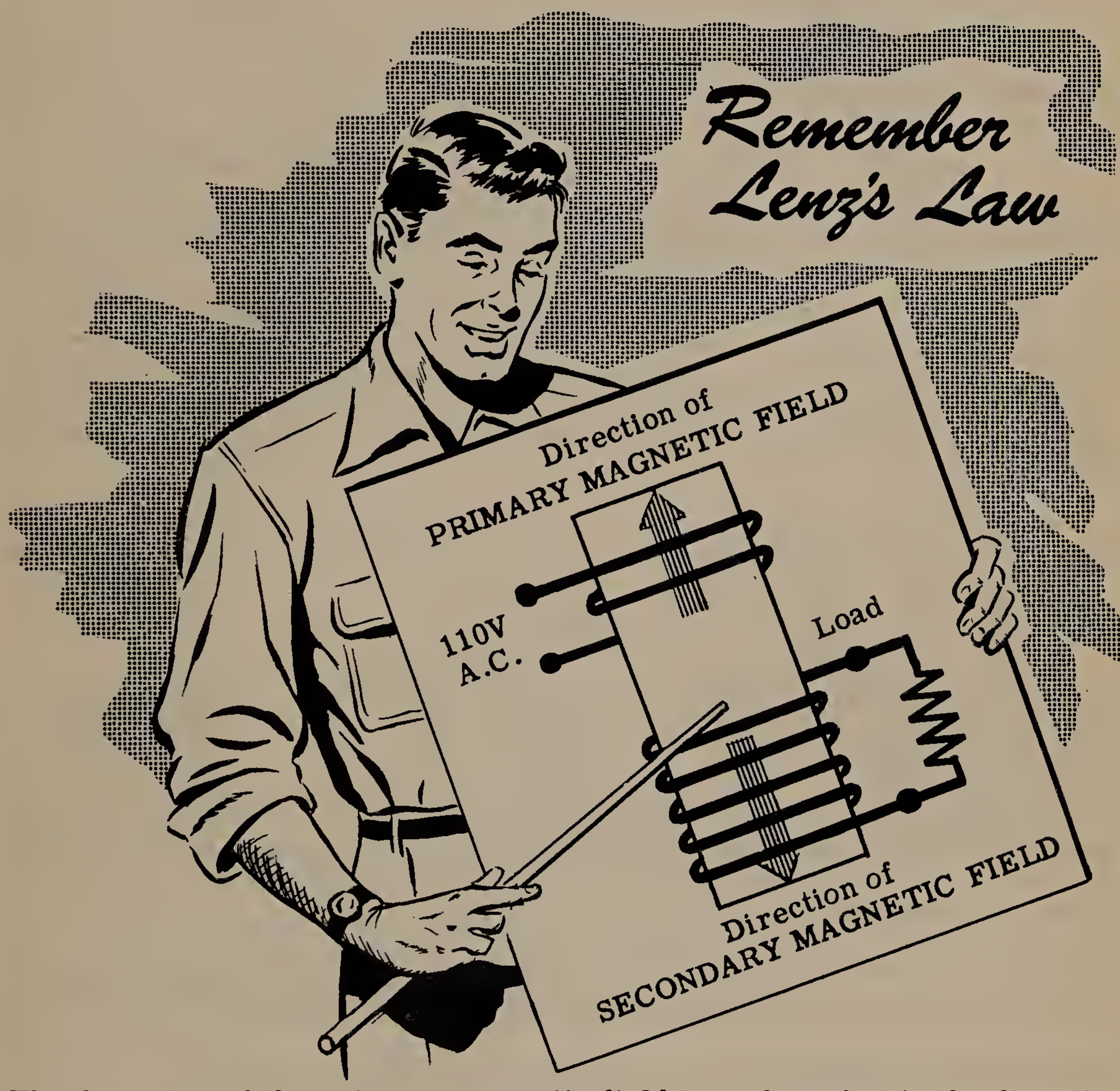
In the above example, the secondary is not connected to a load and there is no current flow. Therefore, no magnetic field can be generated in the secondary, since a magnetic field only exists when there is a current flow. The only magnetic field is that generated in the primary winding.

Now take a look at a synchro generator whose rotor has 110 volts AC applied to it and whose secondary is left open. The same reasoning applies here as in the case of the transformer. The only magnetic field generated is in the rotor and can be represented by an arrow pointing up.



Simple Transformer Theory (continued)

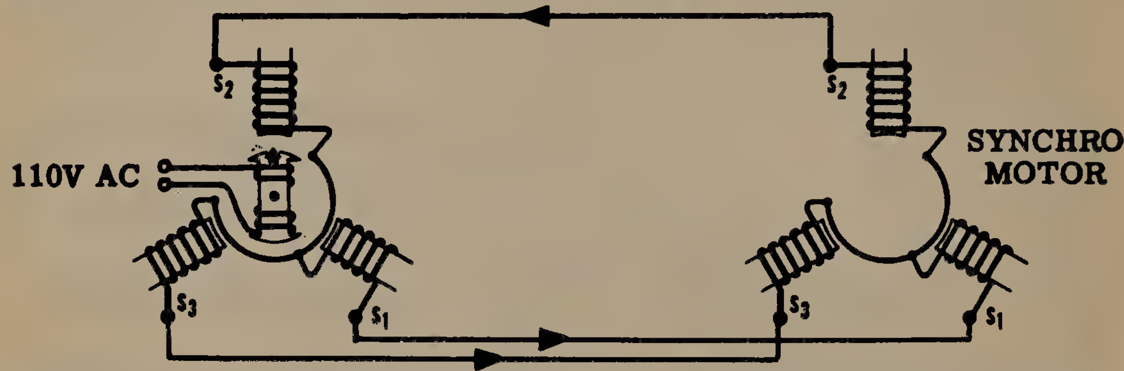
If a load is connected across the secondary of the transformer, a current will flow in the secondary circuit. This current will build up a magnetic field about the secondary winding just as the primary current builds up a magnetic field about the primary winding.



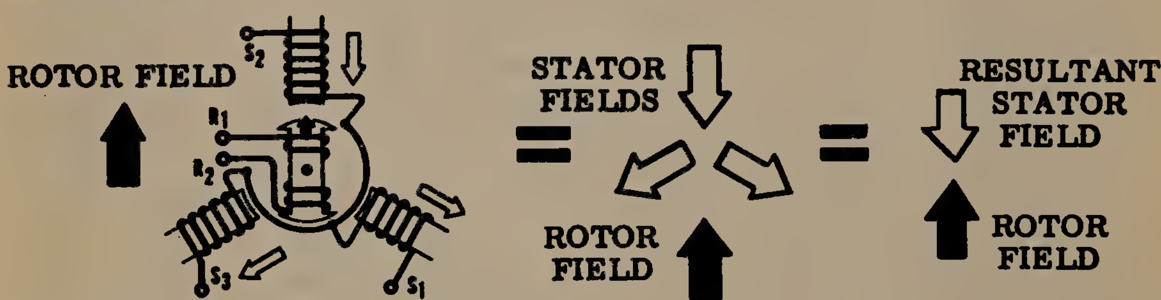
The direction of the primary magnetic field is up but what is the direction of the secondary magnetic field? In order to answer this question, consider first the current flowing in the secondary. This current is caused to flow by the induced voltage generated in the secondary windings by the cutting action of the primary magnetic field. Now, according to Lenz's law, whenever a magnetic field cuts through a coil and induces a voltage in the coil which causes a current to flow, that current will in turn generate its own magnetic field which will oppose the original inducing magnetic field. In other words, the magnetic field generated in the secondary will be in exactly the opposite direction as the primary magnetic field. This is shown by having the arrow of the secondary magnetic field going in the opposite direction to the arrow of the primary magnetic field.
Now that you know the direction of the magnetic fields in a transformer, you can go back to the synchros and see how they work.

How the Synchro Generator-Motor Team Works

Suppose we connect a load across the three stator windings of a synchro generator. Let this load be the stator windings of a synchro motor.



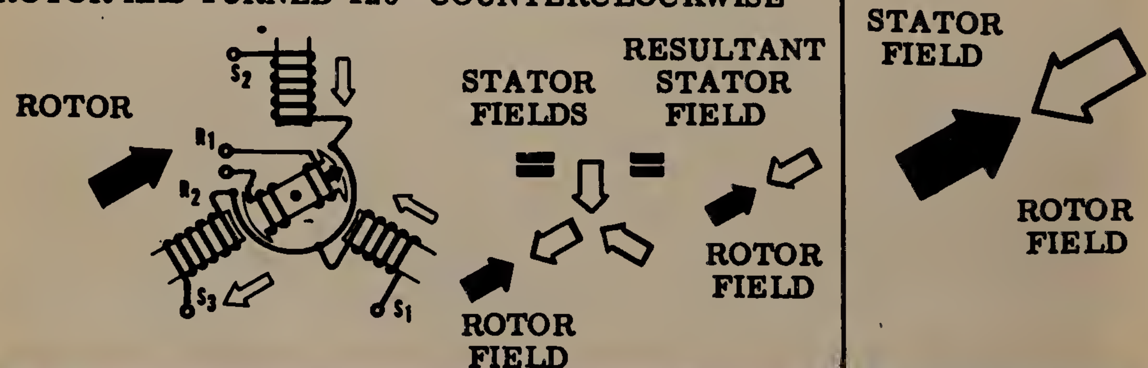
The magnetic field generated in the rotor will induce a voltage in each of the stator windings by transformer action and cause currents to flow as shown. These currents flowing in the three windings S_1, S_2 and S_3 will generate three magnetic fields. These three magnetic fields will combine together to produce one resultant field just as was done with the three bar magnets.



Notice that this resultant magnetic field is exactly in the opposite direction as the original magnetic field in the rotor. This is correct according to Lenz's law which states that the resultant magnetic field must always oppose the inducing magnetic field of the rotor.

If the rotor of the generator is turned to any angle, the resultant magnetic field of the stator will <u>always</u> oppose the magnetic field of the rotor.

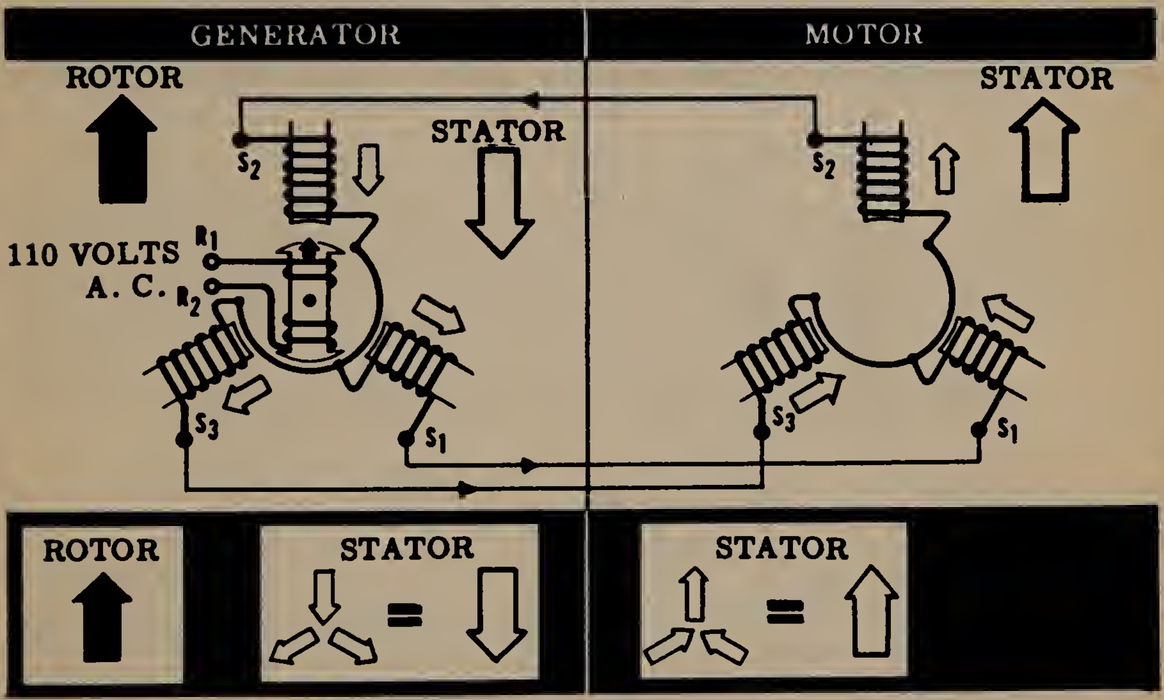
ROTOR HAS TURNED 120° COUNTERCLOCKWISE



ROTOR AND STATOR FIELDS ALWAYS **OPPOSE!**

How the Synchro Generator-Motor Team Works (continued)

The current that flows in stator S_1 of the generator also flows in S_1 of the motor. This current flows up in the generator winding and down in the motor winding. Since both S_1 coils are wound in the same direction, the magnetic fields will lie in opposite directions. Similarly the magnetic field generated in S_2 of the motor will lie in the opposite direction to the magnetic field generated in S_2 of the generator. The magnetic fields generated in windings S_3 of both motor and generator will also lie in opposite directions. Since the individual fields lie in opposite directions, the resultant fields will also lie in opposite directions. This is shown in the diagram.

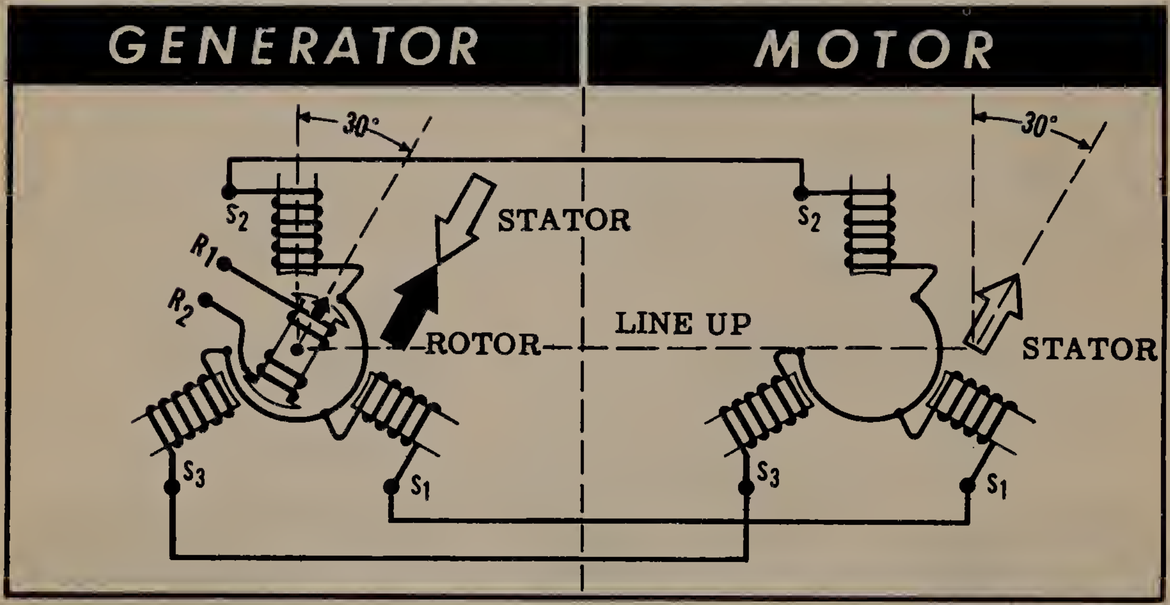


Notice also that the rotor field of the generator and the resultant field of the stators in the motor line up in the same direction. You can easily see that these fields will always line up for any position of the generator rotor when the stators are connected up as shown.

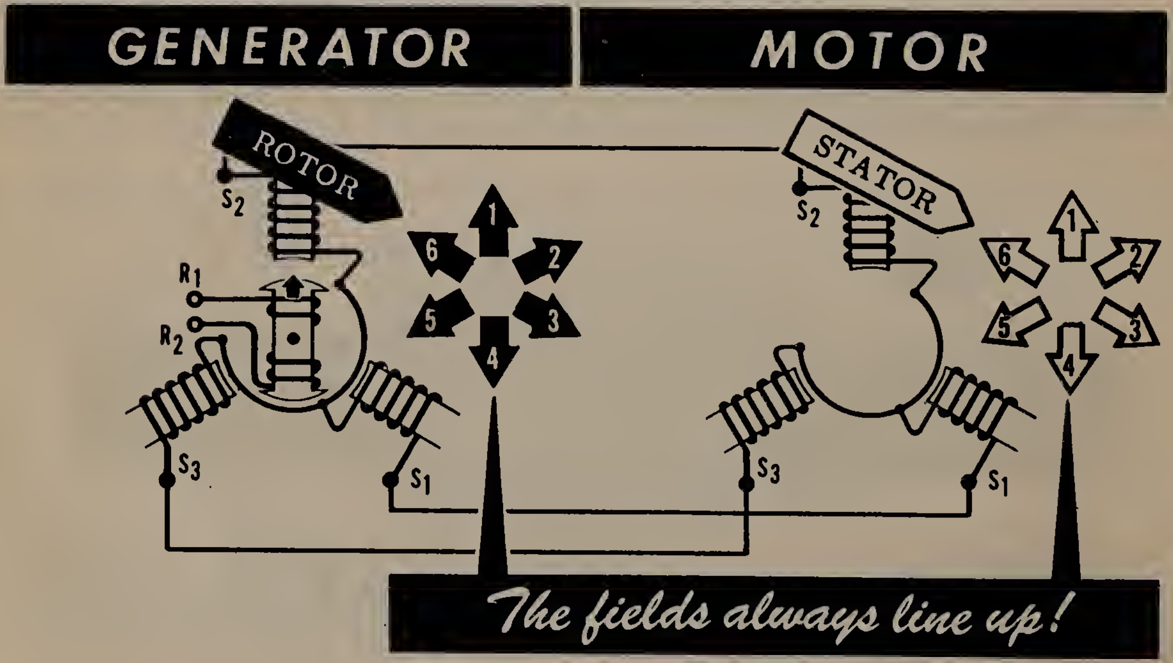
How the Synchro Generator-Motor Team Works (continued)

Let us see what happens as you turn the rotor of the generator.

If you turn the generator rotor 30 degrees clockwise, the magnetic field of the rotor will now be at an angle of 30 degrees. According to Lenz's law, the resultant magnetic field generated in the stator must oppose the original magnetic field. The stator magnetic field will therefore also rotate 30 degrees so that it still opposes the original magnetic field. Since the currents flowing in the motor stator are equal but opposite in direction to the currents flowing in the generator stator, the resulting magnetic field generated in the motor stator will oppose the generator stator field and line up with the generator rotor field.

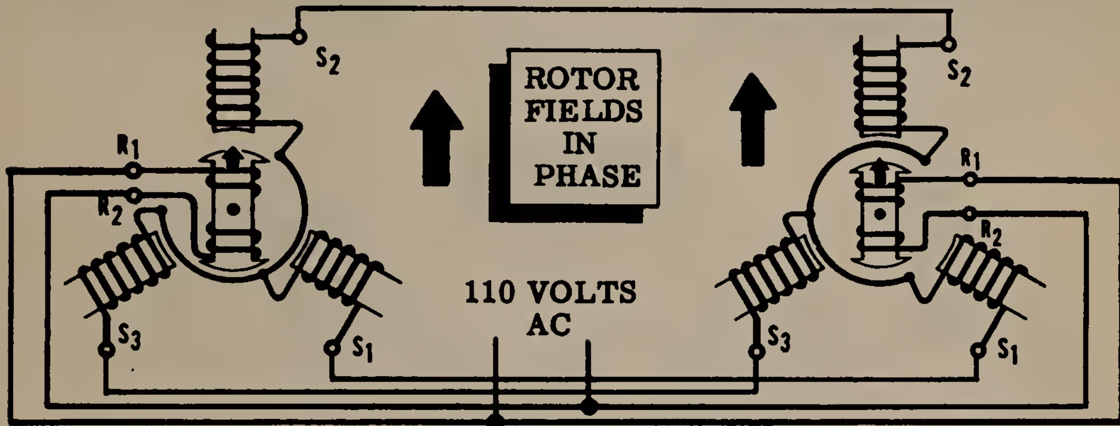


Since you know that the motor stator field and the rotor generator field always line up, you immediately know the direction of the motor stator field once you are given the direction of the generator rotor field.

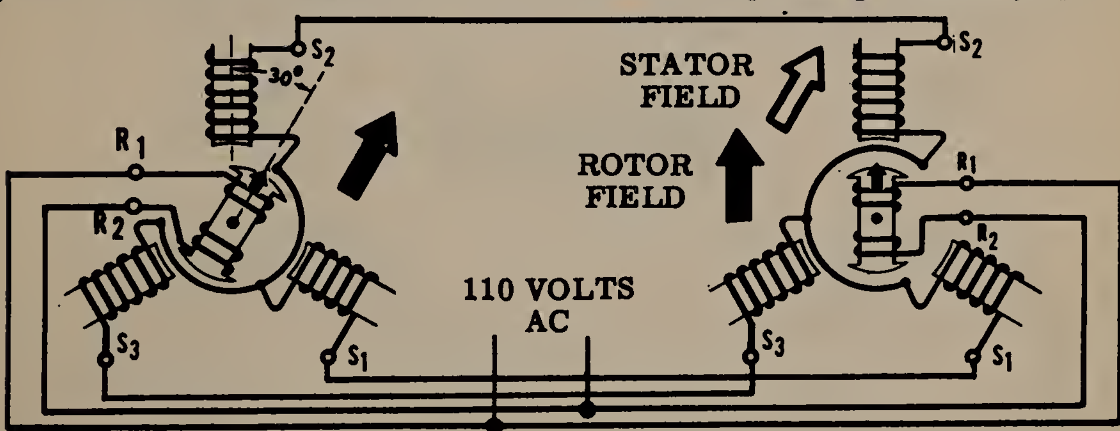


How the Synchro Generator-Motor Team Works (continued)

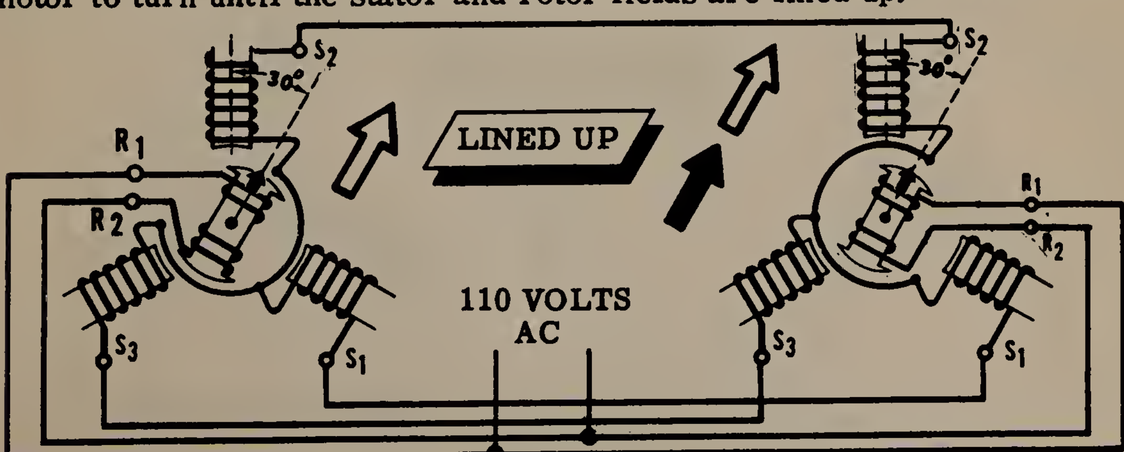
Suppose you consider now the motor with its rotor in place. If the rotors of both generator and motor are connected up in parallel as shown, the magnetic fields generated in both rotors will be in phase, that is, the fields will always point in the same direction from R_2 to R_1 as shown.



If the rotor of the generator is suddenly turned 30 degrees clockwise, the initial condition will have the stator field of the motor displaced 30 degrees from the vertical with the rotor field still pointing vertically up.

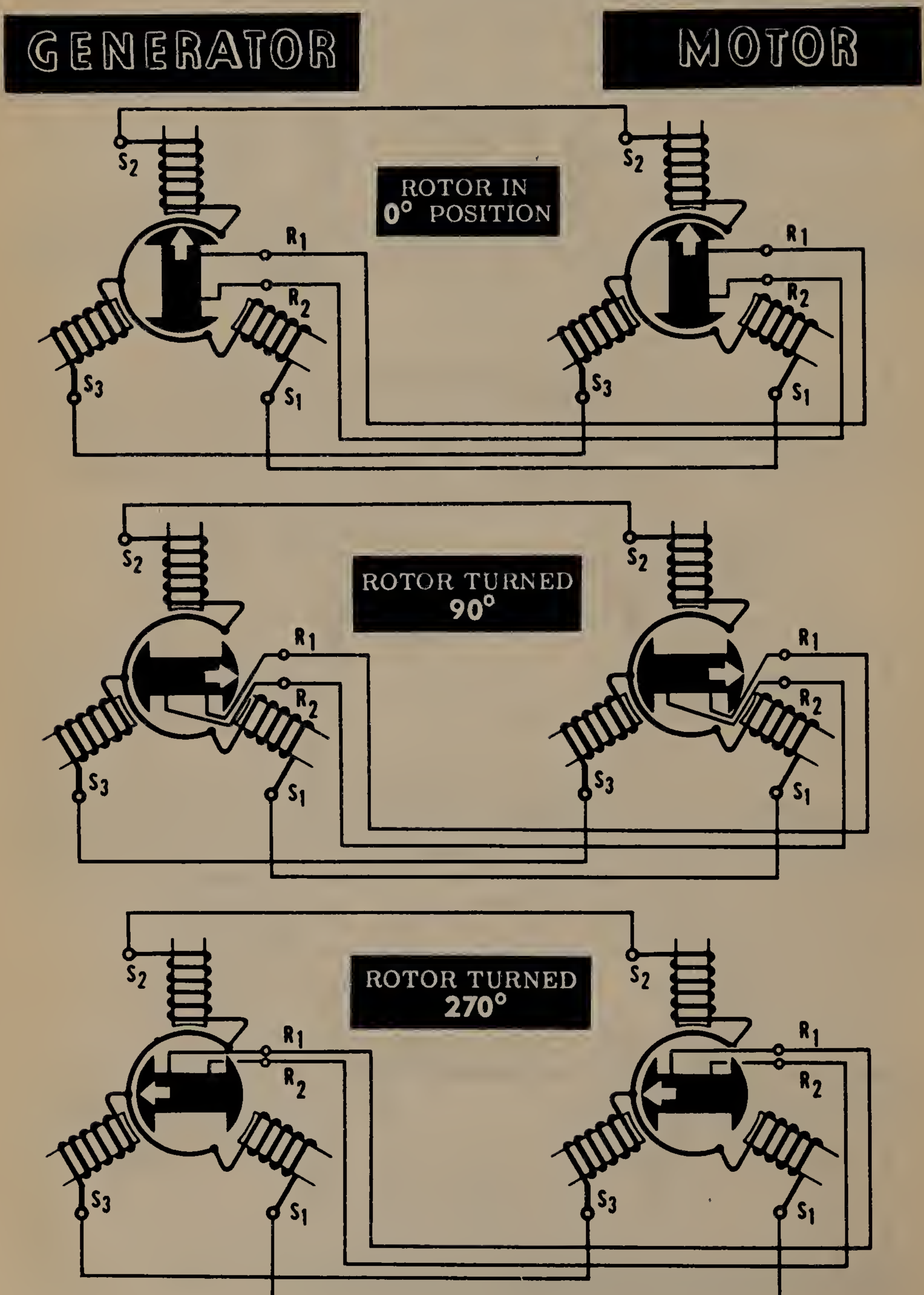


Since the two magnetic fields in the motor are out of line, a strong force of attraction will exist which will tend to bring the magnetic fields into line. The magnetic fields will attract each other causing the rotor of the motor to turn until the stator and rotor fields are lined up.



How the Synchro Generator-Motor Team Works (continued)

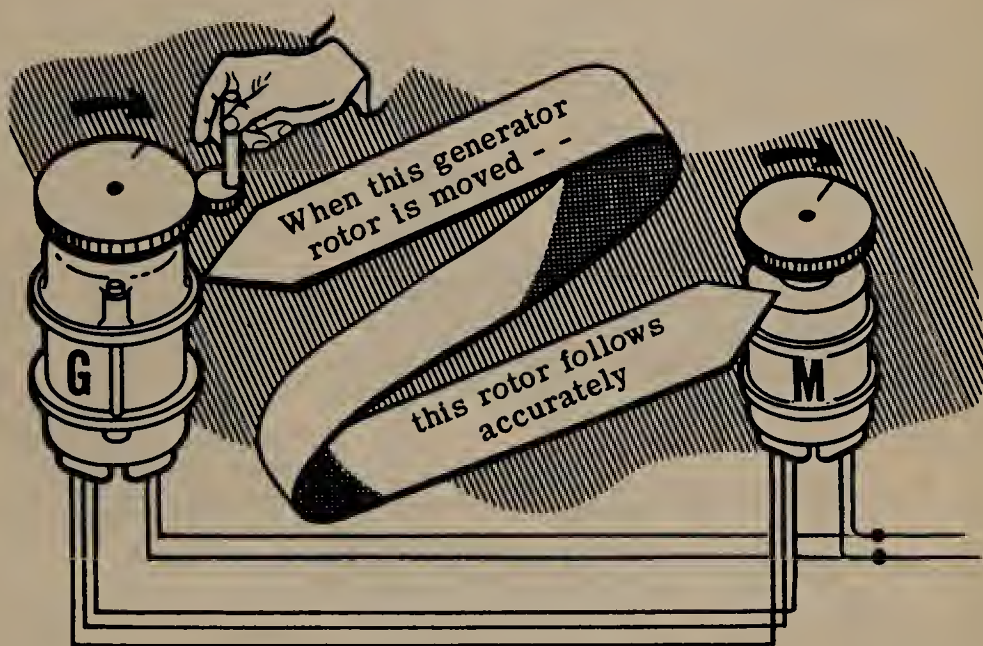
You can see that for every position of the generator rotor, the motor shaft will follow and duplicate the position of the generator shaft.



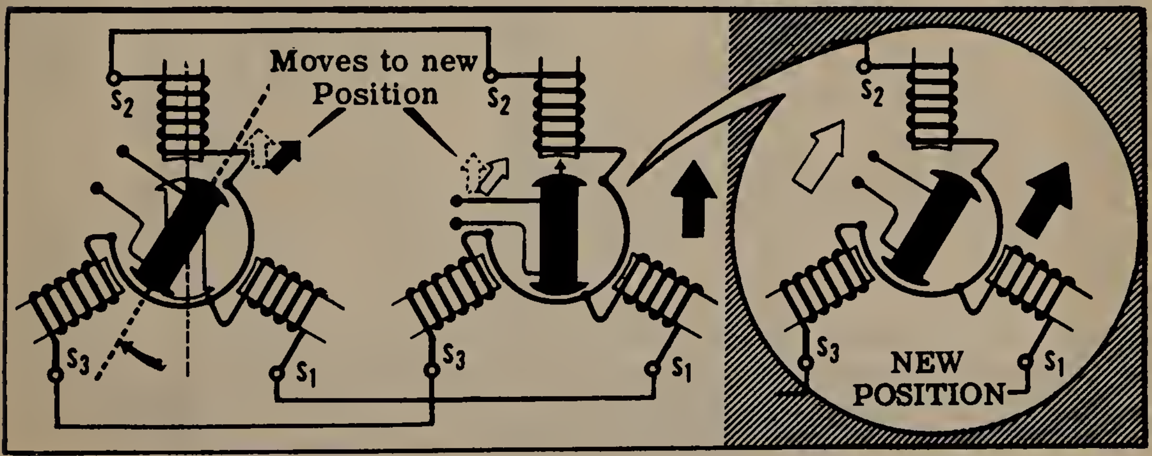
Review of How Synchro Generators and Motors Work

You have just gone through a thorough analysis of how a synchro generator-motor team works. Suppose you very briefly review what you have just learned.

When a synchro system is used to transmit a signal, a movement of the rotor in the synchro generator causes a corresponding movement of the rotor in the synchro motor. The rotor of the synchro motor will always duplicate the position of the rotor in the synchro generator.



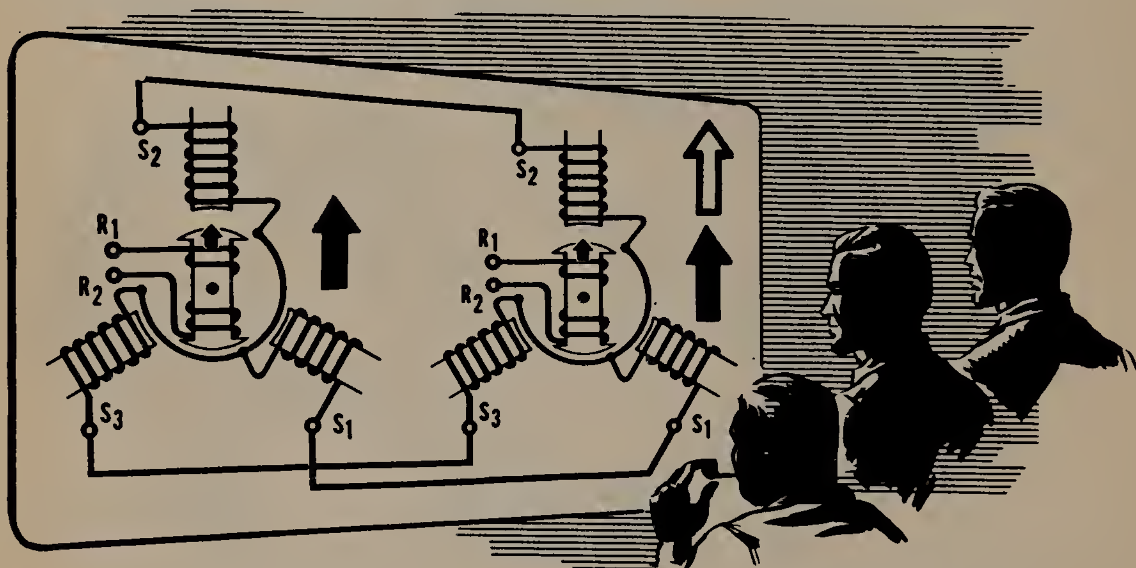
The signal is transmitted electrically from the generator to the motor. What happens is that at the instant the rotor of the generator is turned, currents start flowing in the stator windings. These currents set up resultant magnet fields. The resultant magnetic field in the stator of the motor will always line up with the magnetic field of the rotor. Since the rotors are in phase, the magnetic field in the motor rotor will be attracted to the magnetic field in the motor stator. The result is that the rotor of the motor turns with the rotor of the generator.



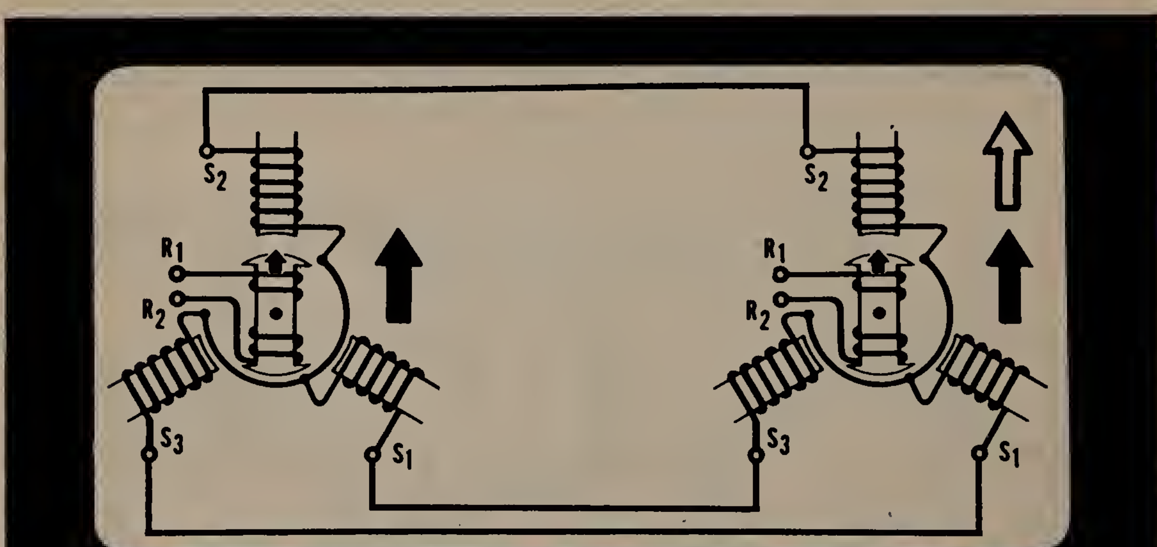
Reversing Stator Connections S_1 and S_3

Now that you have learned about how the rotor of a synchro motor will always duplicate the position of the generator rotor, you may be surprised to learn that the rotor of the motor can also be made to go in the opposite direction to that of the generator rotor.

Shown below is a familiar synchro system where the corresponding stators are connected together. The rotor of the motor lines up with the rotor of the generator and therefore indicates the same angular position. Notice the magnetic fields in the rotor of the generator and motor both line up with stator winding S_2.



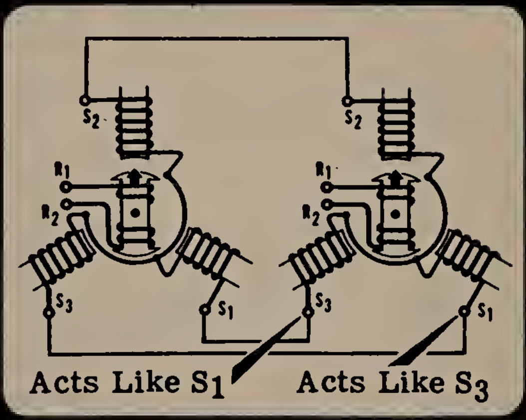
Suppose the connections to S_1 and S_3 are suddenly interchanged so that S_3 and S_1 are connected together. Considering the generator, the magnetic field in the rotor still lies midway between S_1 and S_3. The resultant field in the stator of the motor will likewise do the same and there will be no change in the position of the motor rotor.



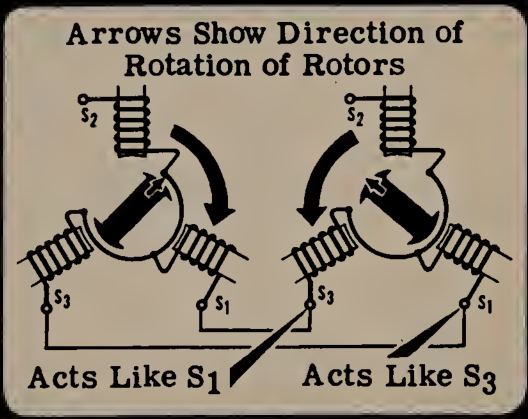
REVERSING STATOR CONNECTION S_1 AND S_2

Reversing Stator Connections S_1 and S_3 (continued)

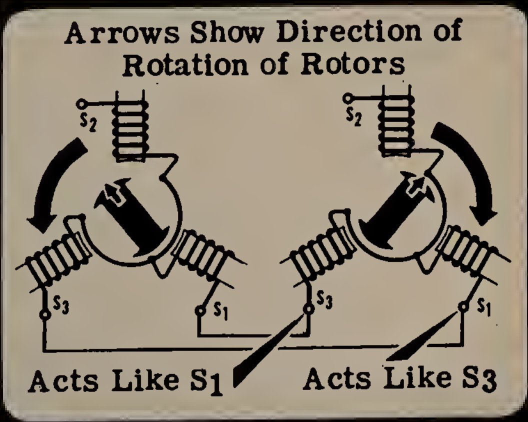
Since winding S_3 of the generaator is now in series with winding S_1 of the motor, the same current will flow in both windings and, therefore, the same magnitude of magnetic field will build up in both windings. Winding S_1 of the motor acts therefore just as if it were labeled S_3—however it is displaced from the usual position of winding S_3 by 120 degrees. Similarly, winding S_3 of the motor acts just as if it were labeled S_1.



If the generator shaft is turned clockwise, so that it rotates from S_2 toward S_1, the resultant field in the stator of the motor will also rotate from S_2 toward the effective S_1. Notice that in order to turn from S_2 to S_1 the rotor will have to turn counterclockwise, just opposite to the rotation of the generator rotor.

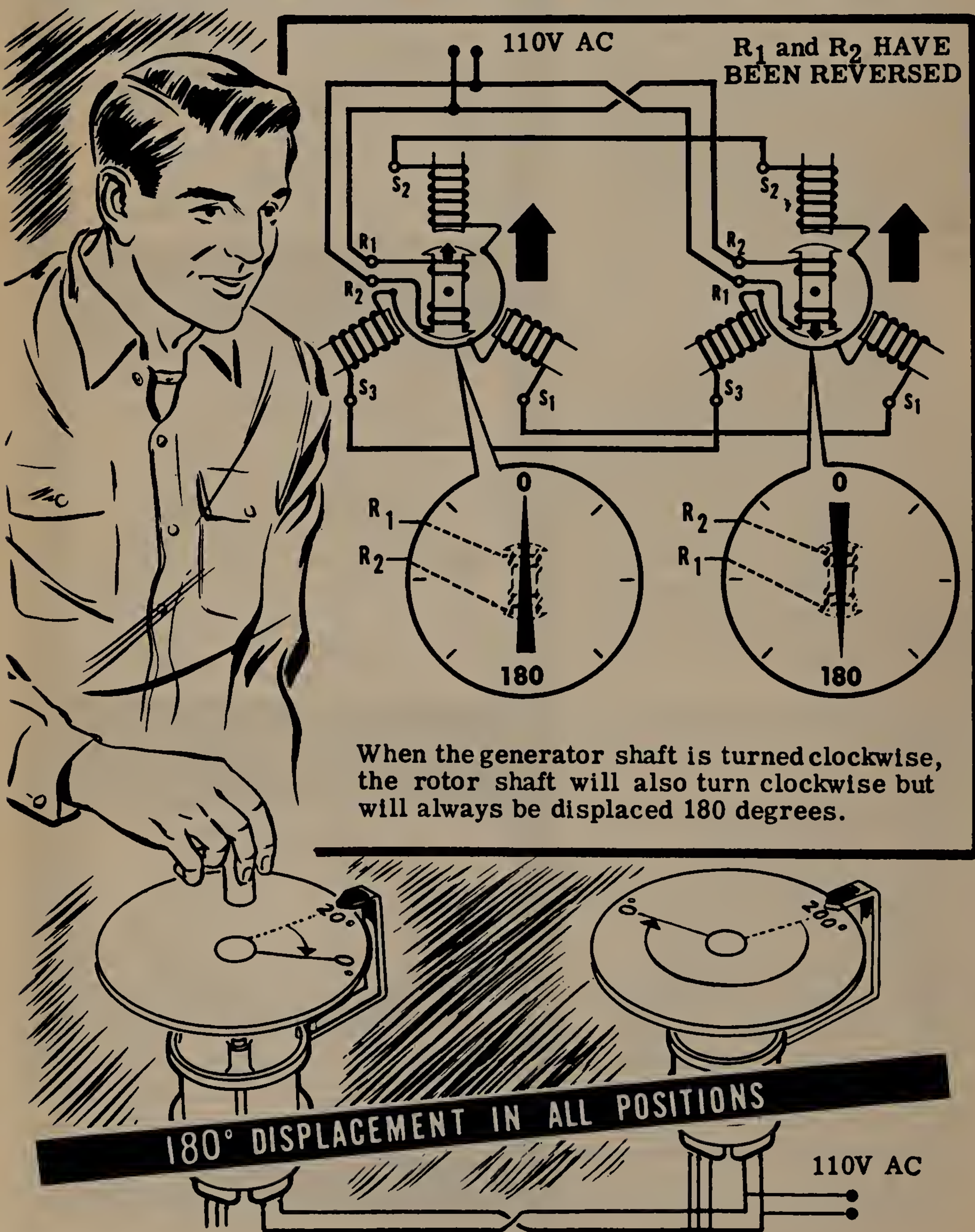


With the above connection the motor's shaft will always turn opposite to the generator's shaft, and the position of the motor's shaft can be determined by subtracting the generator's position from 360 degrees. Connections S_1 and S_3 are the only ones that are ever interchanged in a standard synchro to cause a reversal in rotation of the motor shaft.



Reversing Rotor Connections

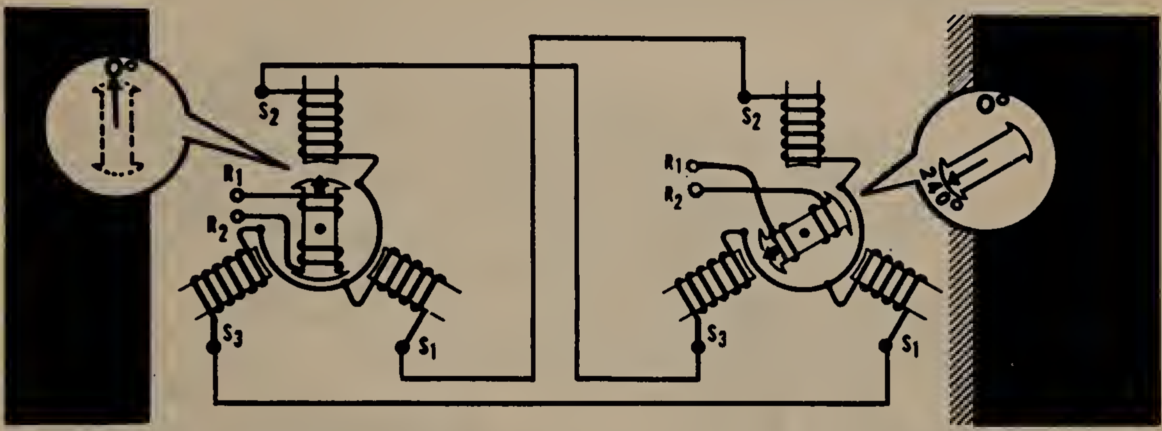
You should also know that the effect of reversing the rotor connections of either the motor or the generator is to cause a 180-degree displacement between both shafts, with both shafts still rotating in the same direction. If R_1 and R_2 of the motor are reversed, the direction of the magnetic field in the motor rotor will reverse. In order for the now reversed rotor magnetic field to line up with the stator field, the motor rotor must rotate through 180 degrees as shown. Thus, when the generator shaft reads zero degrees the motor shaft will read 180 degrees.



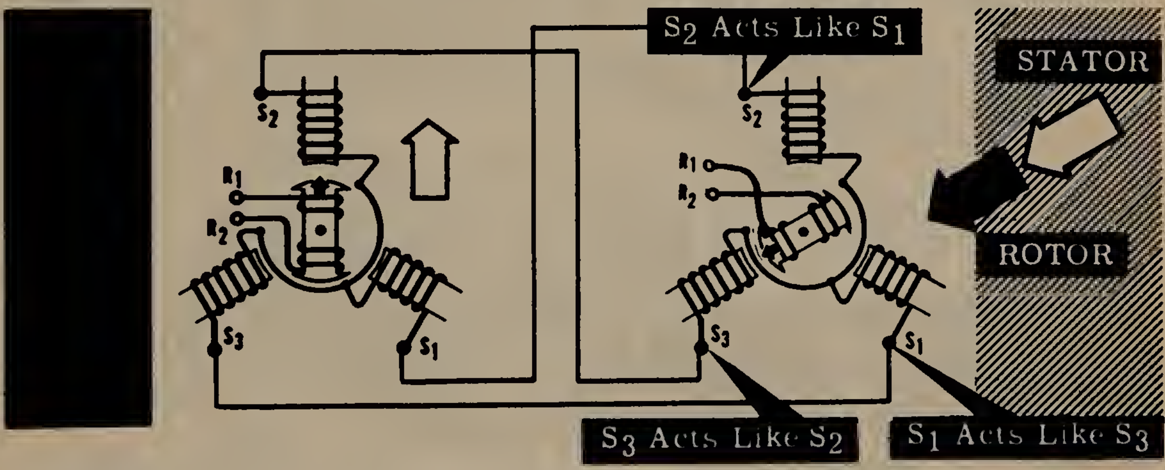
When the generator shaft is turned clockwise, the rotor shaft will also turn clockwise but will always be displaced 180 degrees.

Cyclic Shift of Stator Connections

Suppose all the stator leads are shifted so that S_1 connects to S_2, S_2 connects to S_3 and S_3 connects to S_1. The result of this change is to cause the motor rotor shaft to be displaced 240 degrees clockwise from the generator shaft, with both shafts still rotating in the same direction.



Since S_1 of the generator connects to S_2 of the motor, S_2 acts electrically as if it were an S_1 winding. Similarly, S_3 is effectively an S_2 winding and S_1 is effectively an S_3 winding. Since the magnetic field of the generator rotor lies parallel to S_2, the resultant magnetic field generated in the stator of the motor will also be parallel to the effective S_2 winding.

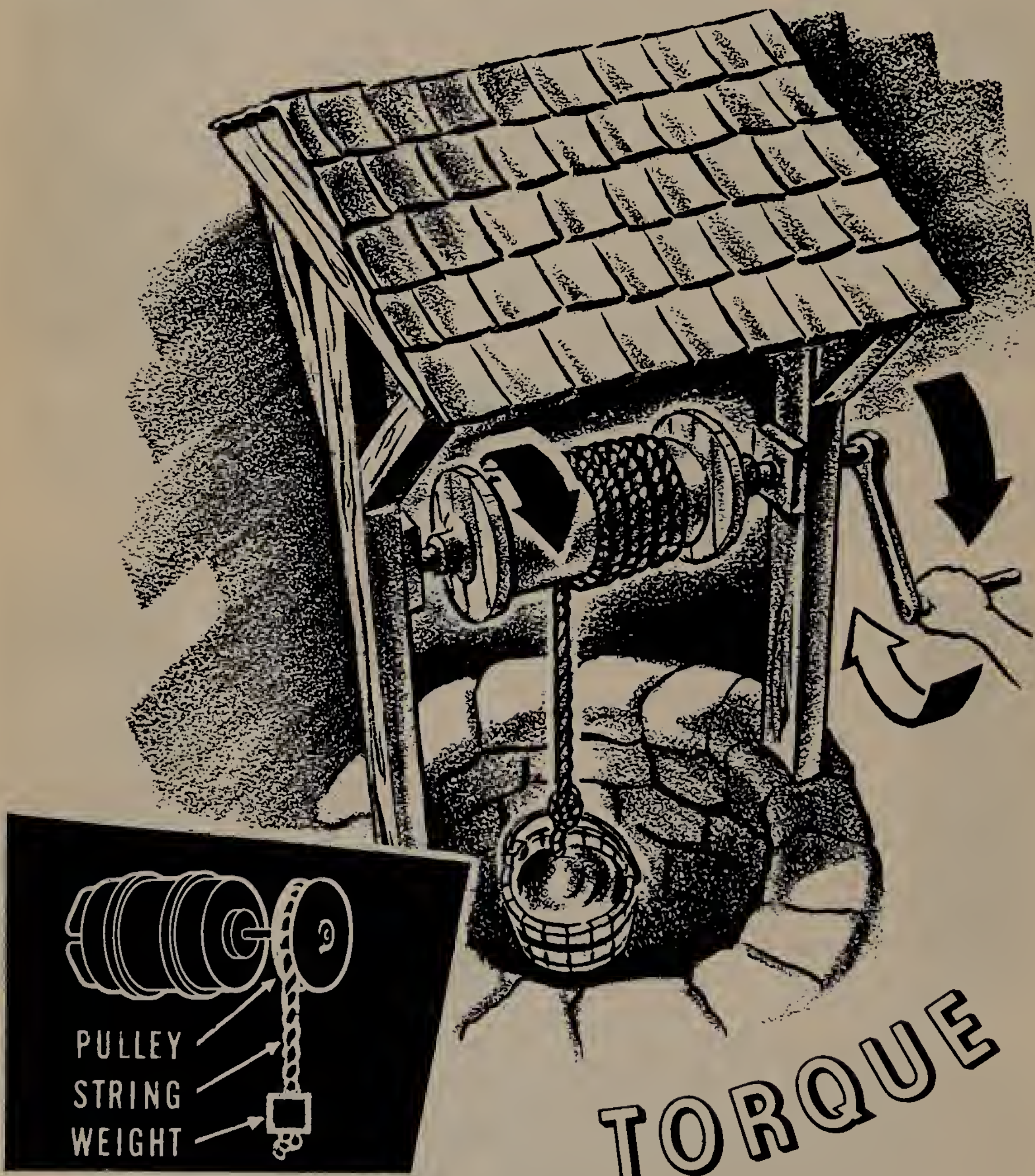


This magnetic field will attract the rotor of the motor and cause it to line up as shown. When the shaft of the generator rotor is turned clockwise, it will turn in the direction of S_2 to S_1. The resultant stator field of the motor will also turn in the direction of the effective S_2 to S_1 (or from actual S_3 to S_2). The rotating magnetic field will attract the rotor and cause it to follow the field exactly.

You have seen how the motor shaft can be made to reverse its direction, or to rotate in the same direction at a fixed error angle from the generator shaft. Suppose you now find out something about how large a turning force can be exerted by a synchro motor.

Torque Produced by a Synchro Motor

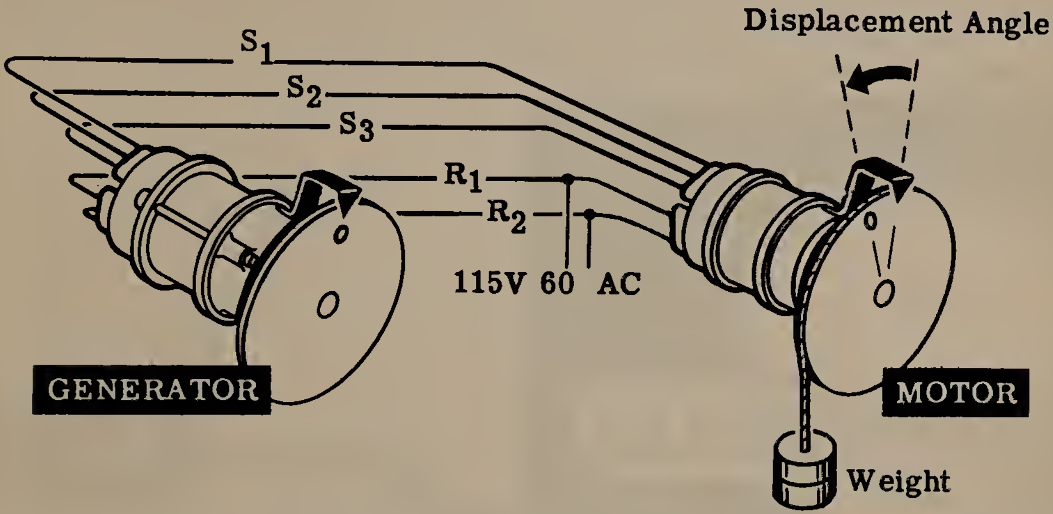
The word torque refers to the twisting force which a driven shaft exerts upon a load. This twisting force, if great enough, will make the load turn with the shaft. A good example of the application of a torque to do work is the well bucket and pulley. By turning the handle a torque is exerted upon the rope which causes it to wrap itself around the drum. In doing so it pulls up the bucket full of water.



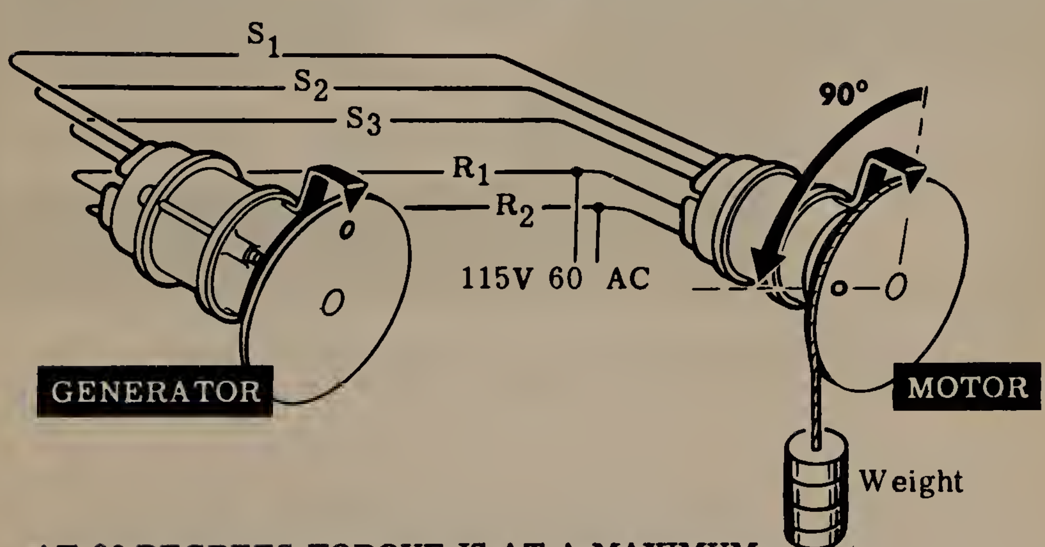
The shaft of a synchro motor similarly produces a torque when the generator shaft is turned. The rotating magnetic field attracts the rotor of the motor causing it to turn and exert a torque on whatever load is connected to its shaft. In the illustration the load on the synchro motor is a pulley with a string and weights attached to it.

Torque Produced by a Synchro Motor (continued)

A factor in the design of synchro systems, (mentioned here only for your general information) is how much the torque load on the motor varies the angular displacement of its shaft from the generator shaft. To measure torque, a synchro motor is connected electrically to a synchro generator whose shaft is held on zero degrees. A pulley is then mounted on the motor's shaft and weights are hung from a cord wrapped around the pulley as shown.



As the number of weights placed on the cord is increased, the shaft of the motor will turn more and more away from the zero position. With no weights on the cord, the motor shaft does not have to support a load. Its shaft remains at zero degrees and no torque is developed. At the 90 degree position the motor shaft is supporting a maximum weight and therefore is exerting a maximum torque; at 180 degrees, the torque exerted is zero.

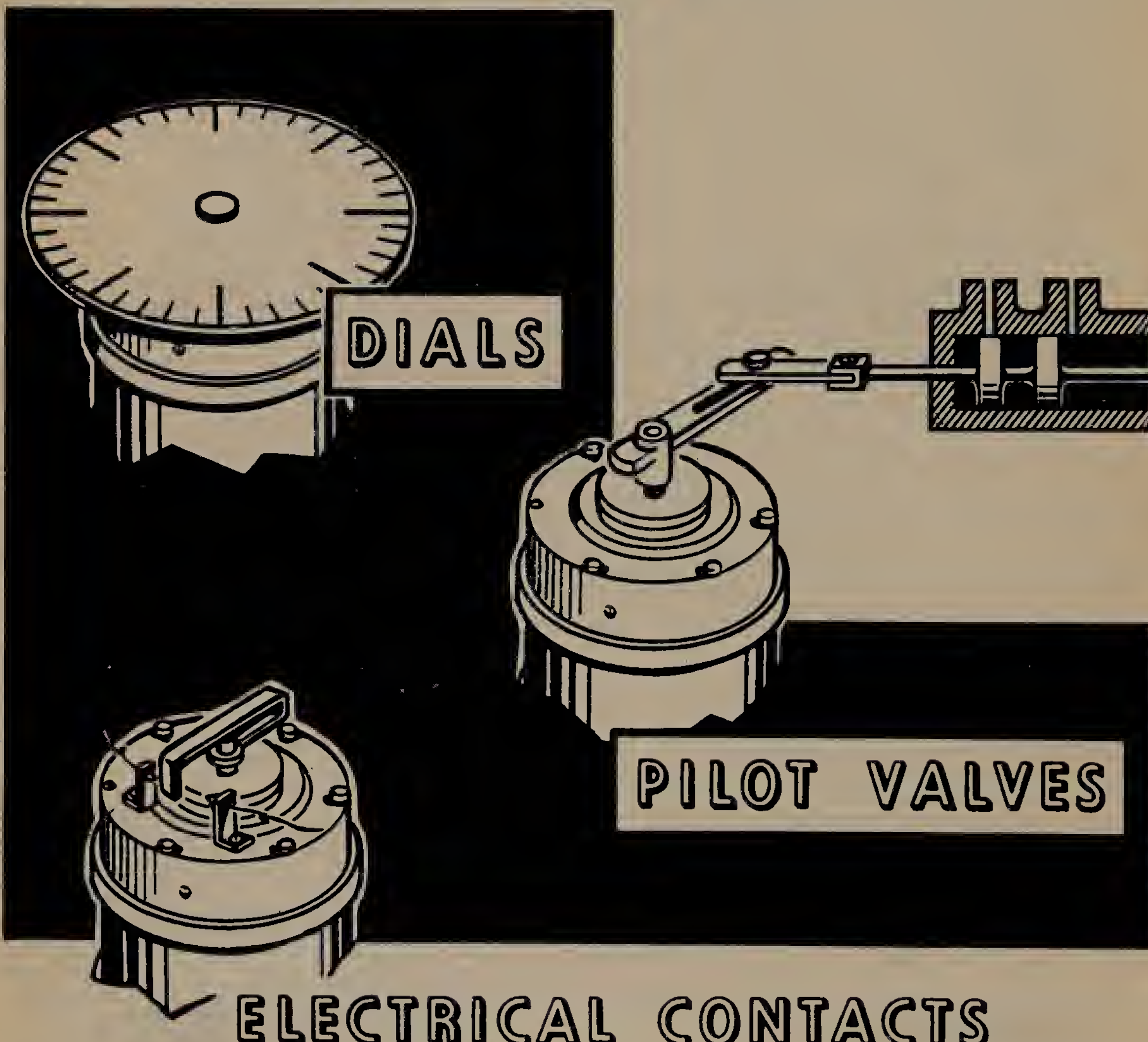


AT 90 DEGREES TORQUE IS AT A MAXIMUM

The problem of the size synchro motor necessary to develop a required torque in a particular application is strictly an equipment design consideration. This problem is solved for you by engineers who always strive to pick out a size motor which will drive the required load with a minimum displacement angle between synchro generator and motor shafts.

Torque Produced by a Synchro Motor (continued)

One of the requirements of a synchro motor is that it be able to position a load with a very small error angle between generator and motor shafts. Since the developed torque is zero when the generator and motor shafts line up, a synchro motor cannot be used to position a comparatively heavy load at or near the equilibrium position without introducing large error angles. As a result, synchro motors are used to perform light operations such as turning a dial, closing electrical contacts or opening and closing the pilot valve of a hydraulic cylinder. Here each load requires a small torque and, therefore, the error angle resulting from producing this amount of torque will be correspondingly small.



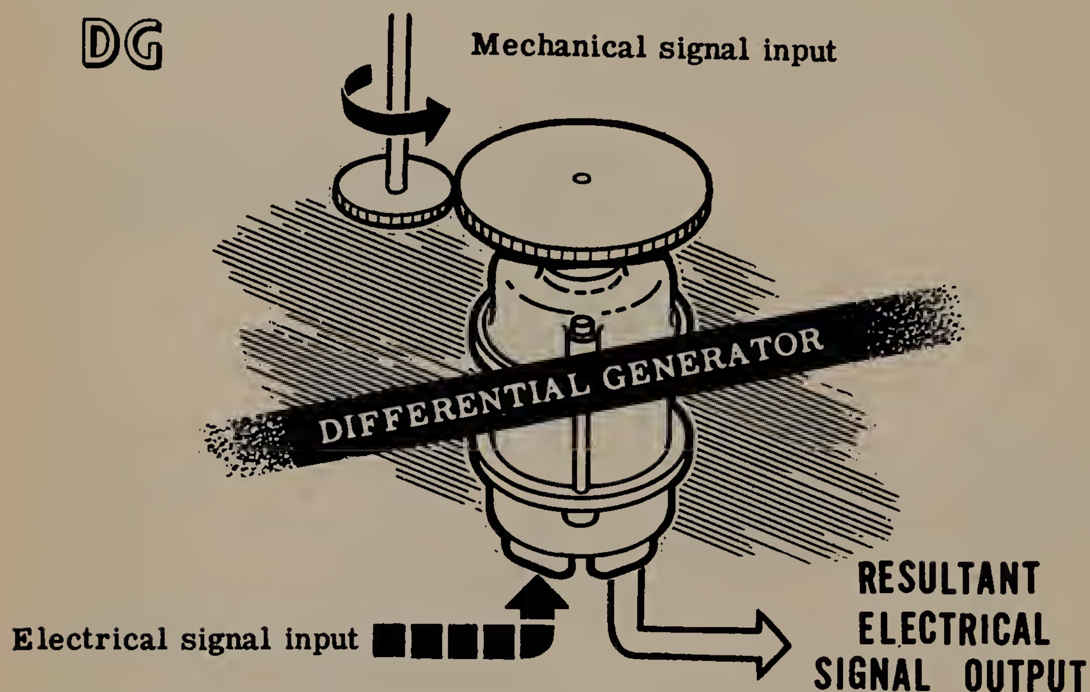
If the final load that is to be moved is an exceedingly heavy one, the synchros are used to control the power input to a driving motor which moves the load. In this case the synchros are part of a complex system called a servomechanism. This you will study later on.

You have just completed studying the operation of synchro generators and motors. The next synchro that you are going to study is the synchro differential.

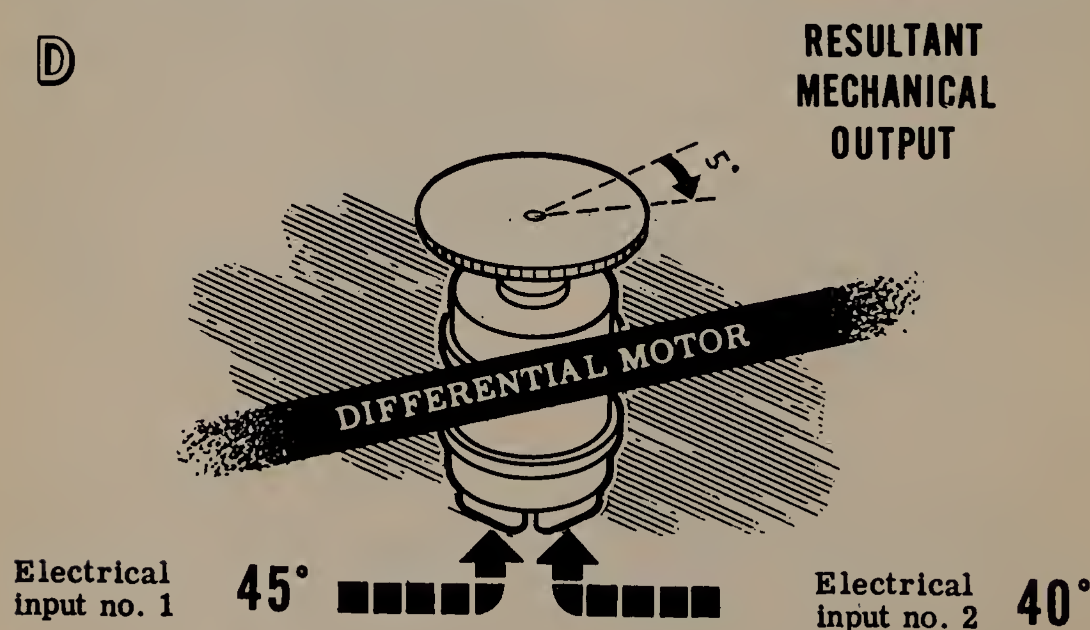
THE SYNCHRO DIFFERENTIAL

General Information

You already know from having read the introduction to this section that a synchro differential can be either a generator or a motor. A synchro differential generator (or DG) can transmit either the sum or difference of two signals, one fed in mechanically, the other fed in electrically from another generator.



The synchro differential motor (or D) can mechanically transmit either the sum or difference of electrical inputs from two synchro generators.



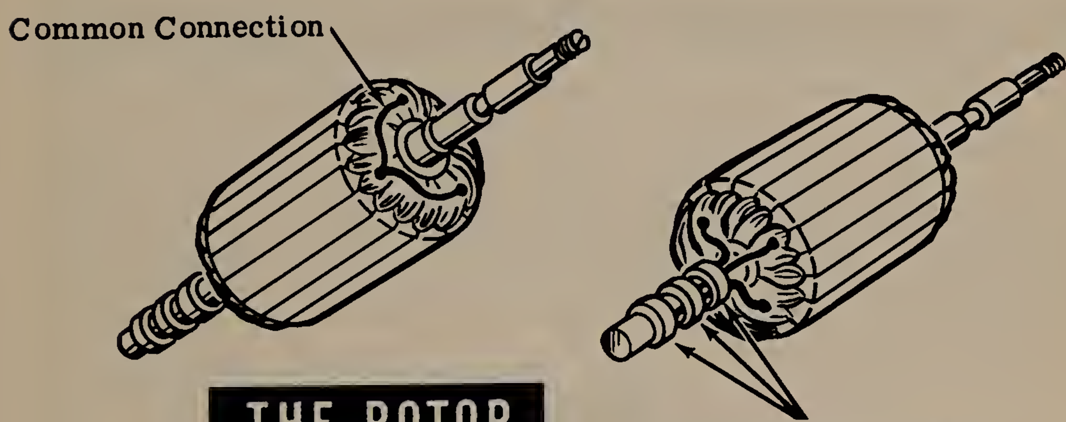
Before you go into the theory of operation of the synchro differential, suppose you study its construction.

Synchro Differential Construction

The synchro differential generator and motor are exactly alike electrically. The only difference in their construction is that the motor has a damper which serves the same purpose as the damper in the synchro motor—it prevents the rotor from oscillating.

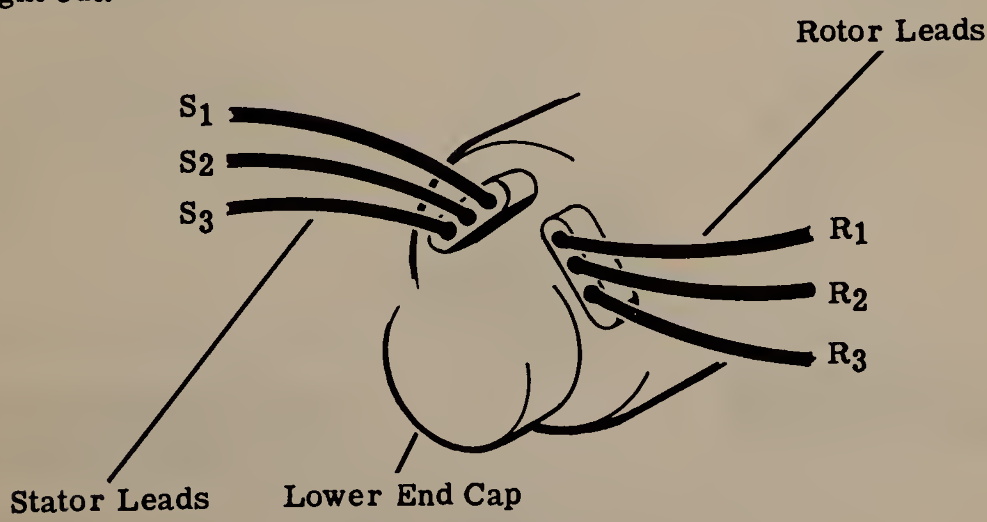
The stator of the synchro differential is the same as the stator of the synchro generator and motor. It consists of three separate coils spaced 120 degrees apart in the stator shell and Y-connected.

The rotor of the synchro differential, unlike the rotor of the synchro generator and motor, consists of three windings instead of the usual single winding. The rotor windings, just like the stator windings, are spaced 120 degrees apart on a slotted core and are Y-connected. One end of each winding is connected to a slip ring on the rotor shaft.



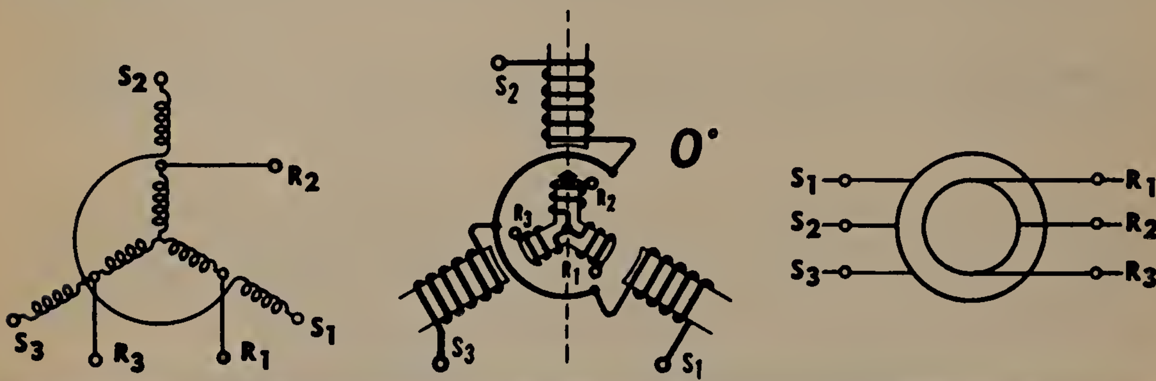
THE ROTOR

In order to make connections to the rotor windings, three brushes are placed in the lower end cap and three rotor leads R_1, R_2 and R_3 are brought out.



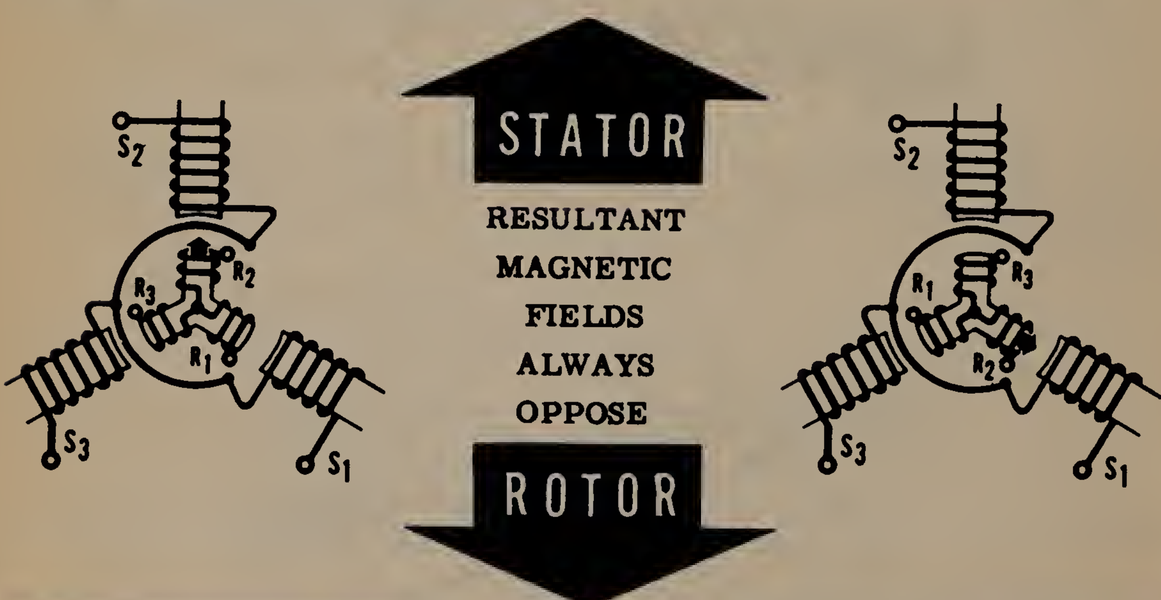
Transformer Action in a Differential

The differential generator can be represented schematically by one of the following three symbols. The rotor is on zero degrees when the R_2 winding lines up with the S_2 winding. The zero position is indicated in schematic B.



A B C

Symbols A and B clearly indicate how transformer action takes place. The stator is the primary and the rotor is the secondary. Electrical signals are transmitted from the primary to the secondary by means of a varying magnetic field cutting through the windings of the rotor. Whenever a resultant magnetic field is generated in the stator windings, it will induce a voltage in the motor windings by transformer action. The induced voltage will cause a current to flow in the rotor which will generate its own magnetic field. This resultant magnetic field will oppose the original inducing field according to Lenz's law.

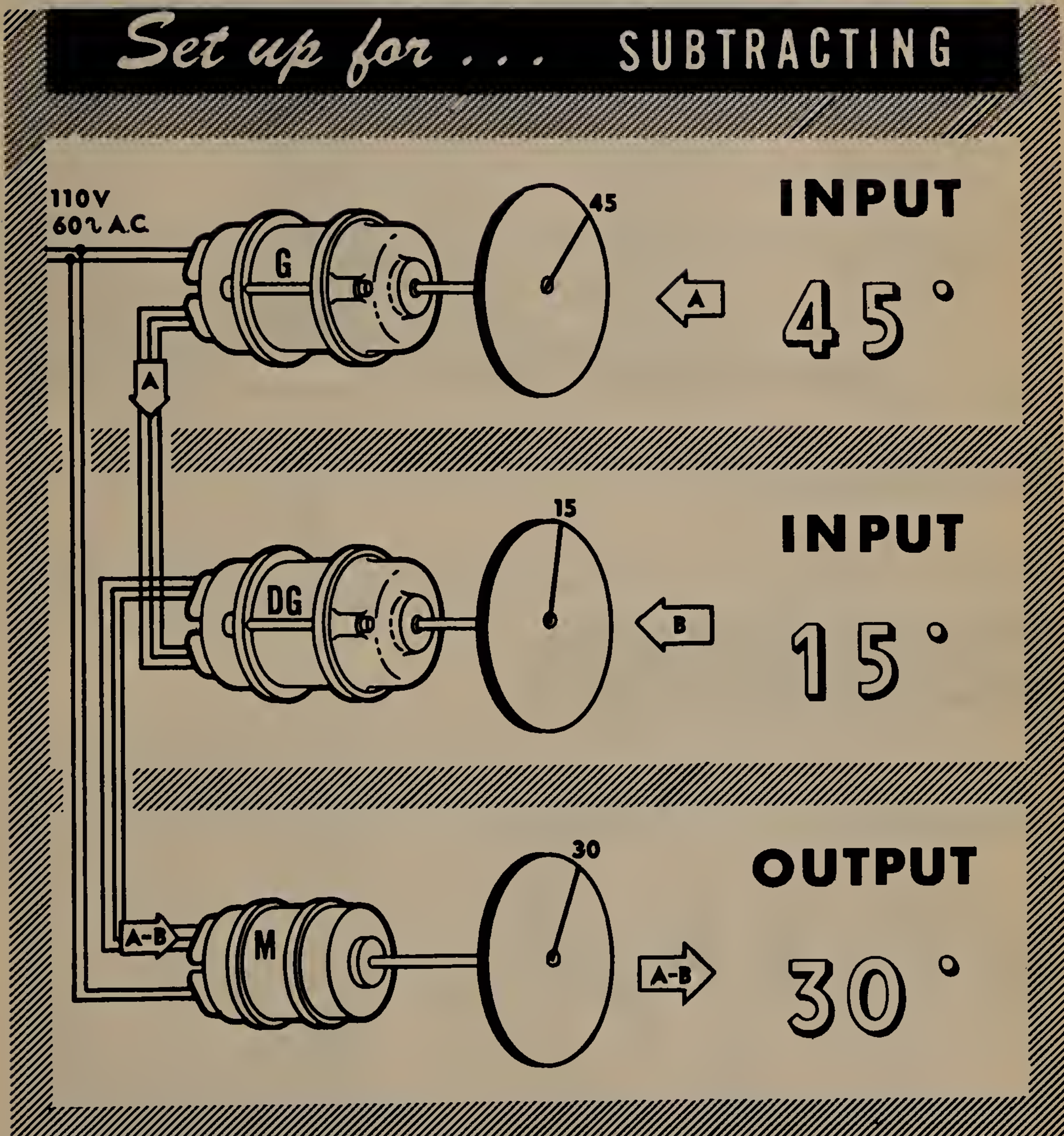


ROTOR-0° ROTOR-120°

The magnetic field generated in the rotor will always oppose the magnetic field in the stator regardless of the position of the rotor.

Differential Generator Subtracting

The diagram shows a three-piece synchro team consisting of a synchro generator, a synchro differential generator and a synchro motor. The stator leads of the synchro generator connect to the stator leads of the differential generator as shown. The rotor leads of the differential generator connect to the stator leads of the synchro motor as shown. Observe that the differential generator does not connect to the 115-volt AC supply. The illustrated connection is the one used to produce a difference output from the two inputs to the differential synchro—the shaft of the DG and the stator of the G.

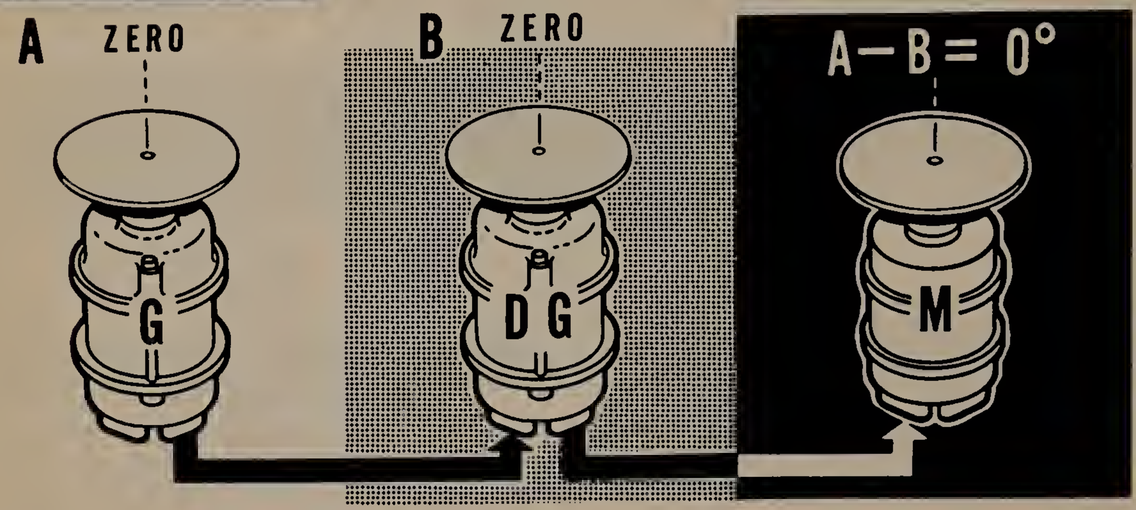


Notice that the signal which is transmitted to the synchro motor is the difference between the electrical signal A and the mechanical signal B. The shaft of the synchro motor will position itself at an angle A-B. In the examples that follow, the letters A and B will always refer to the final positions of the rotors relative to the S_2 reference axis.

Differential Generator Subtracting (continued)

Suppose you go through a number of examples of a three-piece synchro team in action, to see how you can figure out the final position of the motor shaft. The letter G will stand for generator, DG will stand for differential generator, and M will stand for motor.

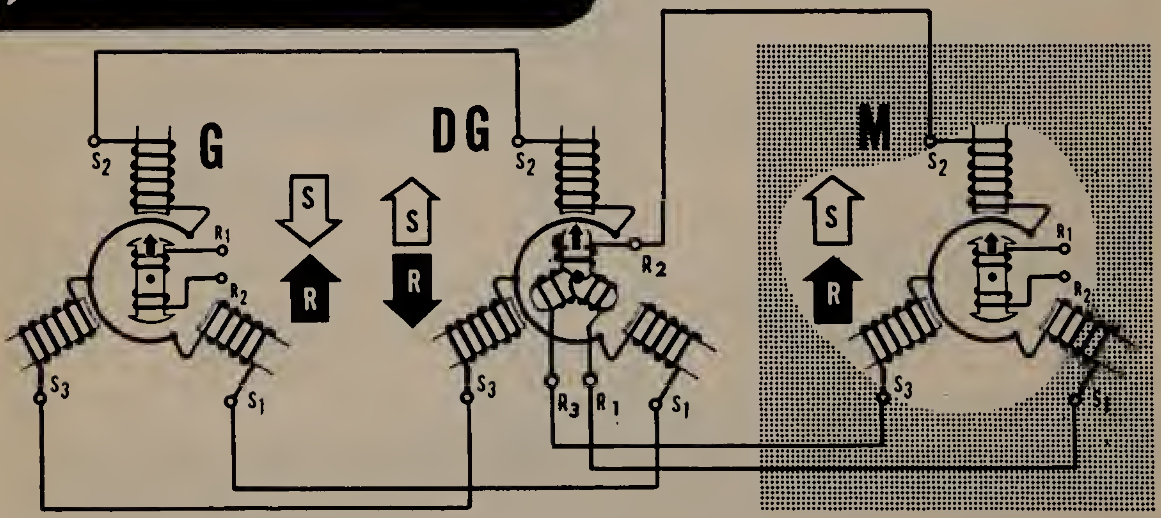
EXAMPLE NO. 1



If both the G and DG rotors are at zero degree, the rotor of the motor will also be at zero degree.

You can easily work out the Example 1, using the familiar magnetic field analysis (S stands for stator field and R stands for rotor field).

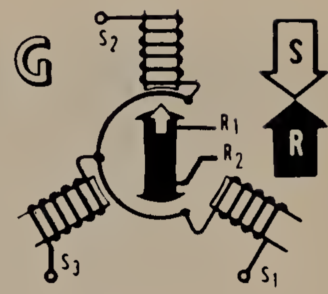
Follow it on the schematic



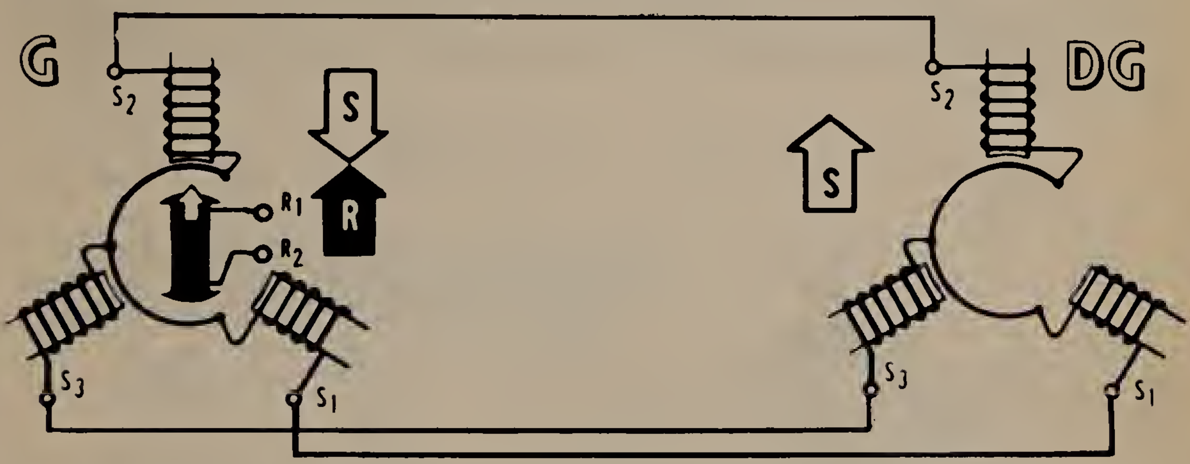
Since the magnetic field in the rotor of the DG lies parallel to R_2, the magnetic field in the stator of the motor will also be parallel to S_2 but will point in the opposite direction. The rotor of the motor will be attracted to the magnetic field in the stator and will line up with it. The details of this analysis will be presented on the next page.

Differential Generator Subtracting (continued)

Since the rotor of the G is on zero degrees, the rotor field will be positioned at zero degrees as shown. The induced magnetic field in the stator of the G will line up with the rotor field and will oppose it in direction.



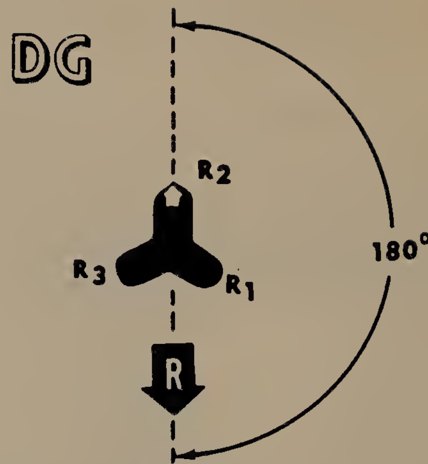
Since the stators of the G and DG are in series, the resulting magnetic field in the stator of the DG will be parallel to the stator magnetic field in the G and will point in the opposite direction, as shown.



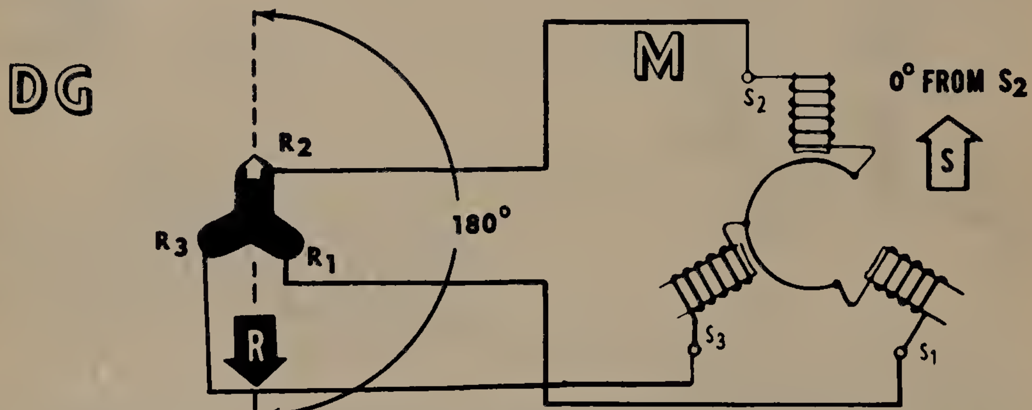
The magnetic field in the stator of the DG will induce a magnetic field in the rotor of the DG. This rotor field will line up with the stator field but will point in the opposite direction as shown.

Differential Generator Subtracting (continued)

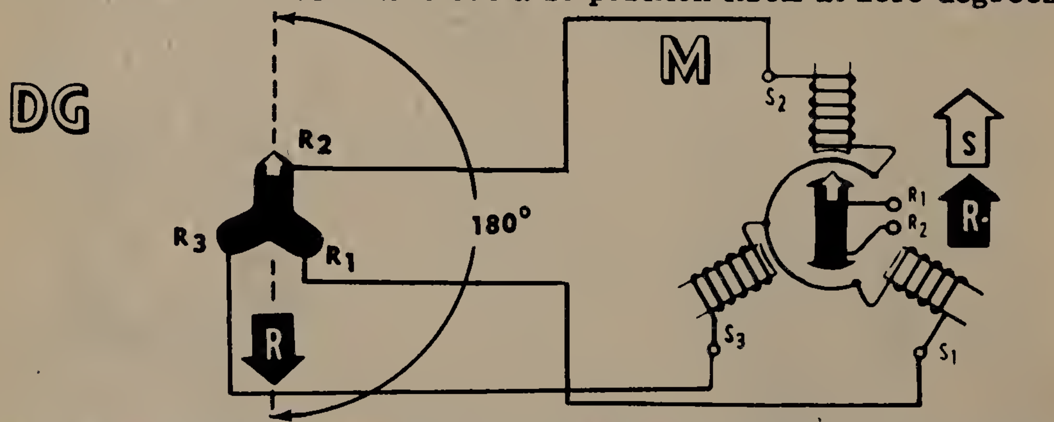
The next thing to do is to determine the angular position of the DG rotor field relative to the R_2 winding. The magnetic field is positioned at 180 degrees in relation to the R_2 winding as shown.



Knowing the angular position of the rotor field relative to R_2, you can immediately tell the position of the stator field in the motor relative to its S_2 winding. This is because the rotor of the DG and the stator of the M are in series, resulting in the two magnetic fields being parallel to each other and pointing in opposite directions. Since the DG rotor field is positioned at 180 degrees, the stator field in the motor will be positioned at zero degrees as shown.



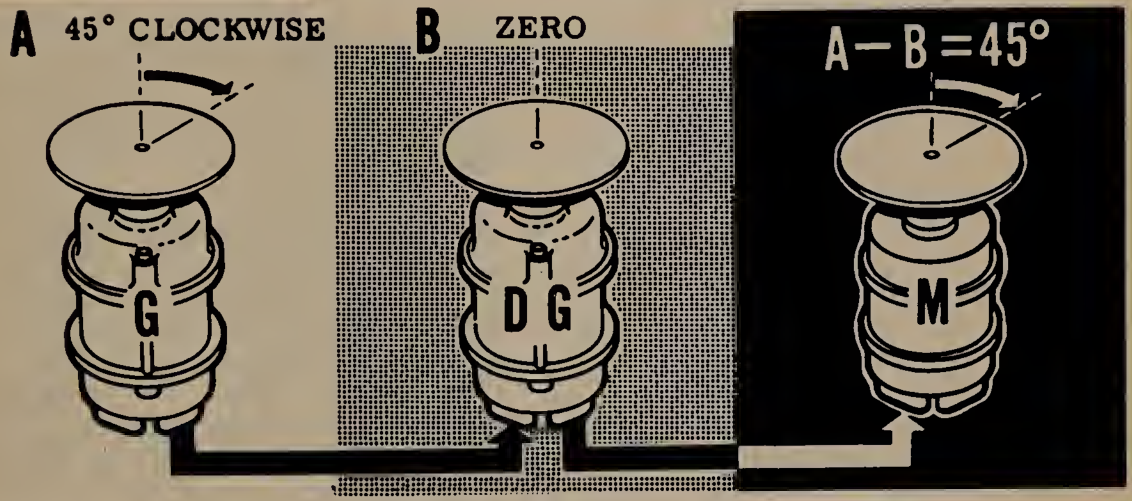
The rotor of the motor will therefore also position itself at zero degrees.



Go over the reasoning presented on this page until you are sure you understand it. This method of analysis should be used whenever you work out problems involving differential synchros.

Differential Generator Subtracting (continued)

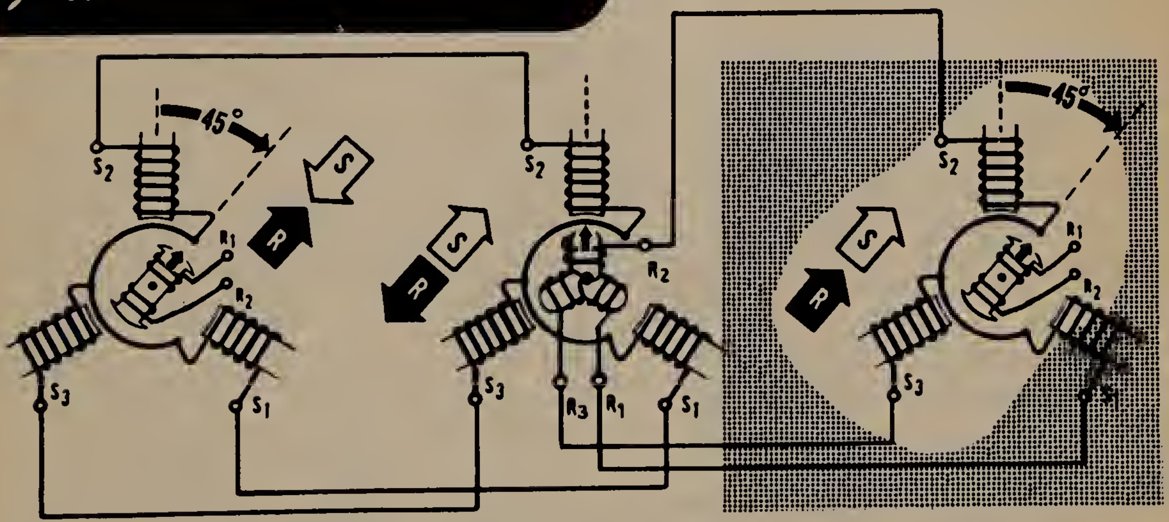
EXAMPLE NO.2



If the DG rotor is held fixed at zero degrees and the generator rotor is turned 45 degrees clockwise, the rotor of the motor will turn 45 degrees clockwise.

Example 2 is worked out below, using magnetic field analysis.

Follow it on the schematic



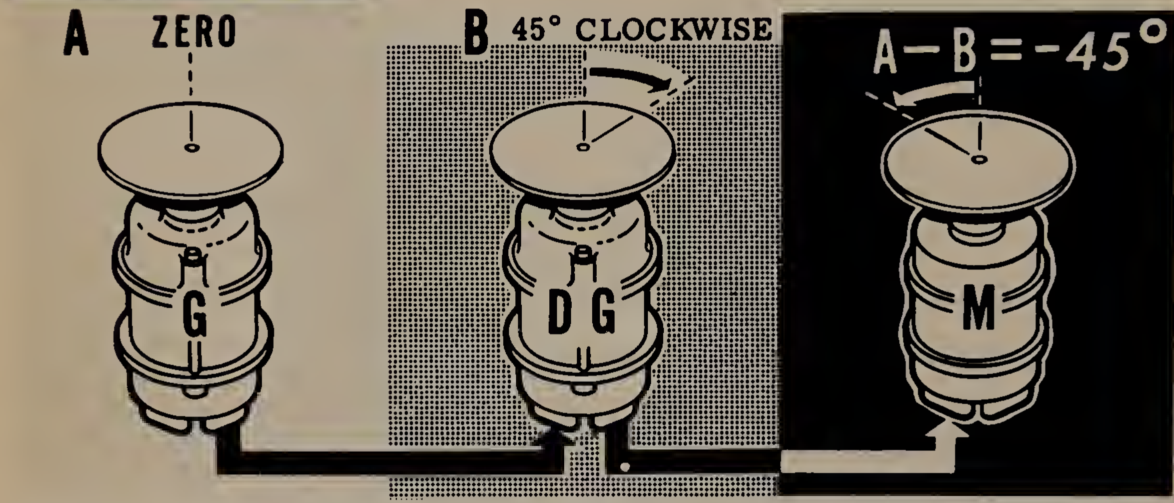
From the previous two examples you can see that when the DG is set on zero (R_2 lined up with S_2), it simply transfers the magnetic field from the generator to the motor without a change in position.

The next examples will illustrate what happens when the rotor of the DG is turned.

Differential Generator Subtracting (continued)

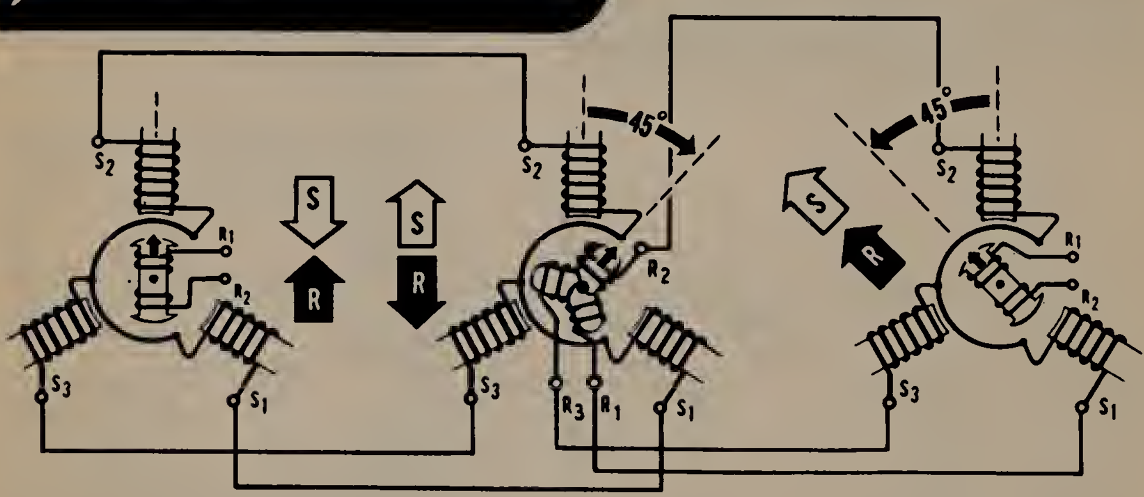
Example 3 is worked out below, using magnetic field analysis.

EXAMPLE NO.3



Since a clockwise rotation is considered positive, an answer like -45 degrees means that the angle is taken in a counterclockwise direction from the reference line. The reference line in all cases is taken to be the axis of coil S_2. In the above example, if the generator is held at zero degree, turning the rotor of the DG clockwise will cause the rotor of the motor to turn counterclockwise by the same amount.

Follow it on the schematic

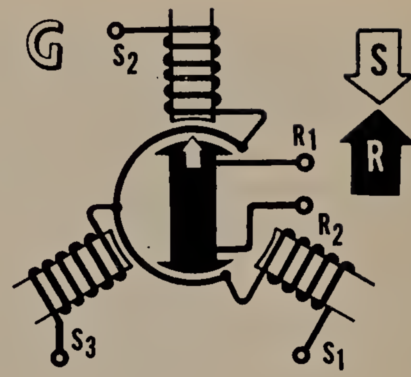


Rotating the rotor of the DG has had no effect on the position of its magnetic field relative to the fixed stator windings.

The position of the magnetic field relative to the stator windings is determined by the setting of the rotor in the generator. However, the position of the magnetic field relative to the rotor windings has changed. Whereas before the magnetic field lined up with R_2, now it lies 45 degrees to the left of R_2. This shift in the position of the magnetic field is duplicated in the stator windings of the motor as shown. The rotor of the motor will line up at the same angle. A detailed analysis of the above problem will be presented on the following page

Differential Generator Subtracting (continued)

Since the rotor of the G is on zero degrees, the rotor field must similarly be positioned at zero degrees as shown. The magnetic field induced in the stator of the G will line up with the rotor field and will oppose it in direction.



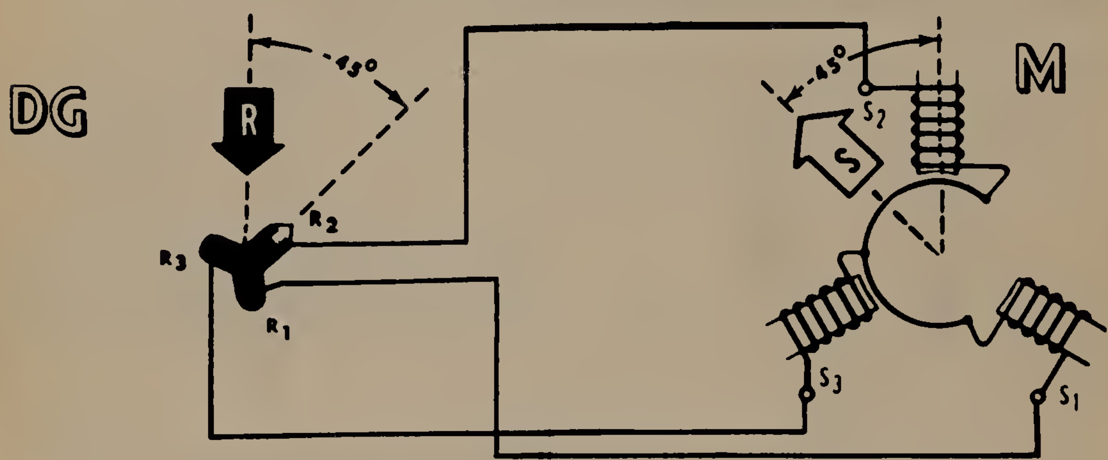
Since the stators of the G and DG are in series, the magnetic field in the stator of the DG will be parallel to the stator magnetic field in the G and point in the opposite direction as shown.

The magnetic field in the stator of the DG will induce a magnetic field in the rotor of the DG. This rotor field will line up with the stator field but will point in the opposite direction as shown.

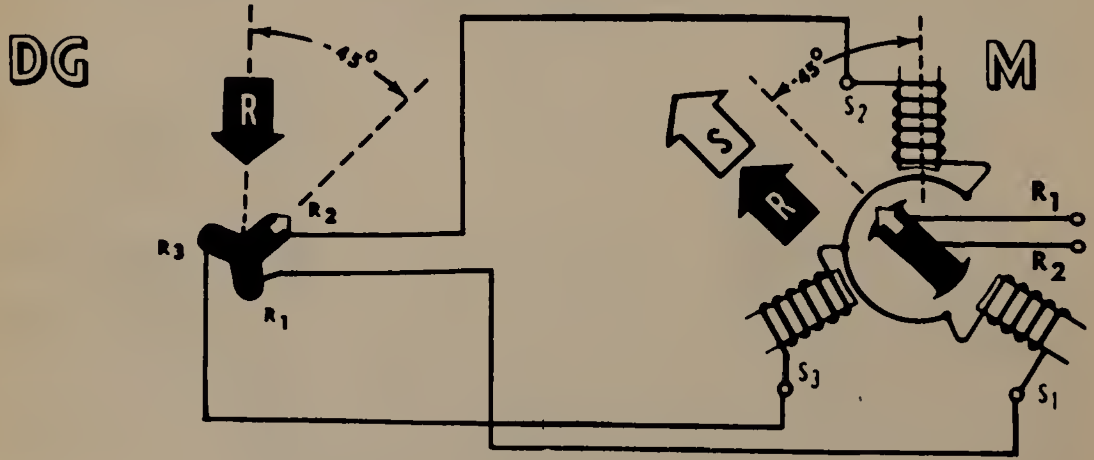
Differential Generator Subtracting (continued)

The next thing to do is to determine the angular position of the DG rotor field relative to the R_2 winding. The diagram shows that the magnetic field is positioned at -45 degrees in relation to R_2 and is pointing down as shown.

Knowing the angular position of the rotor field relative to R_2, you can immediately tell the position of the stator field in the motor relative to its S_2 winding. This is because the DG rotor and the motor stator are in series, resulting in the two magnetic fields being parallel to each other and pointing in opposite directions. The stator field will therefore be positioned -45 degrees relative to its S_2 winding as shown.

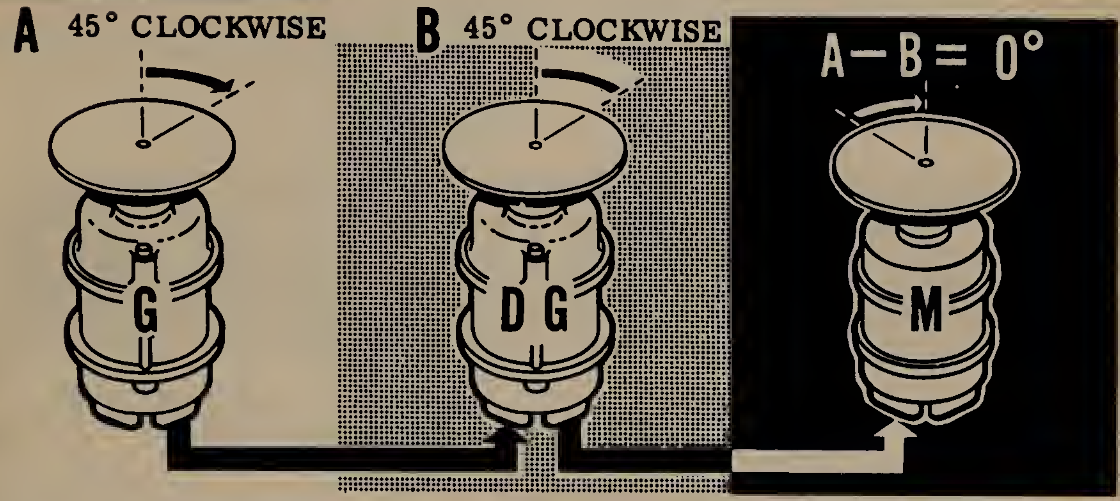


The rotor of the motor will be attracted to the stator magnet field and will also position itself at -45 degrees as shown.



Differential Generator Subtracting (continued)

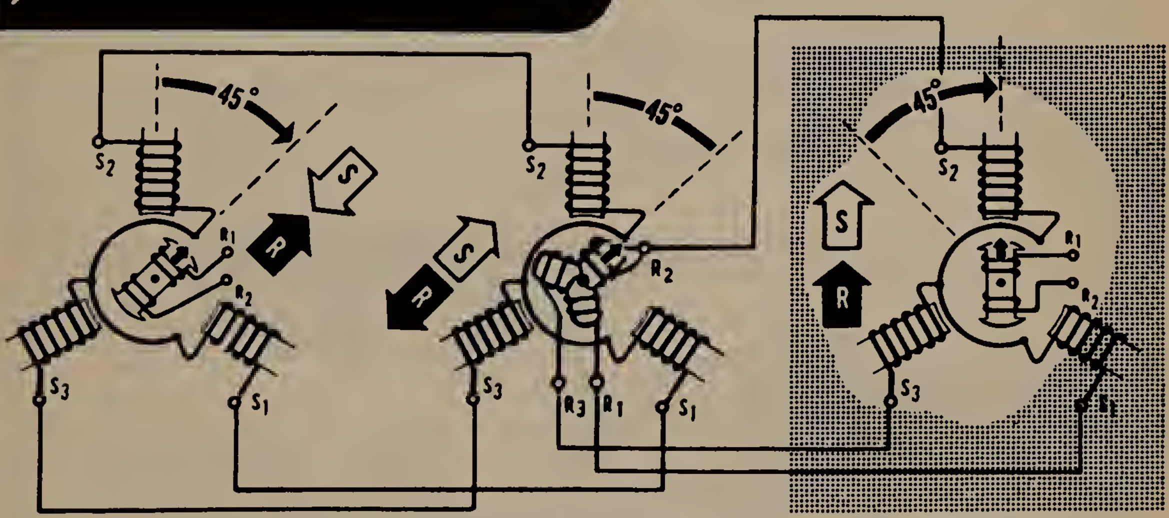
EXAMPLE NO. 4



If now the rotor of the DG is held at 45 degrees and the rotor of the generator is turned to 45 degrees, the rotor of the motor will turn back from -45 degrees to zero degrees. What has happened is that the 45-degree signal from the generator has canceled the signal from the DG.

Example 4 is worked out below, using magnetic field analysis.

Follow it on the schematic

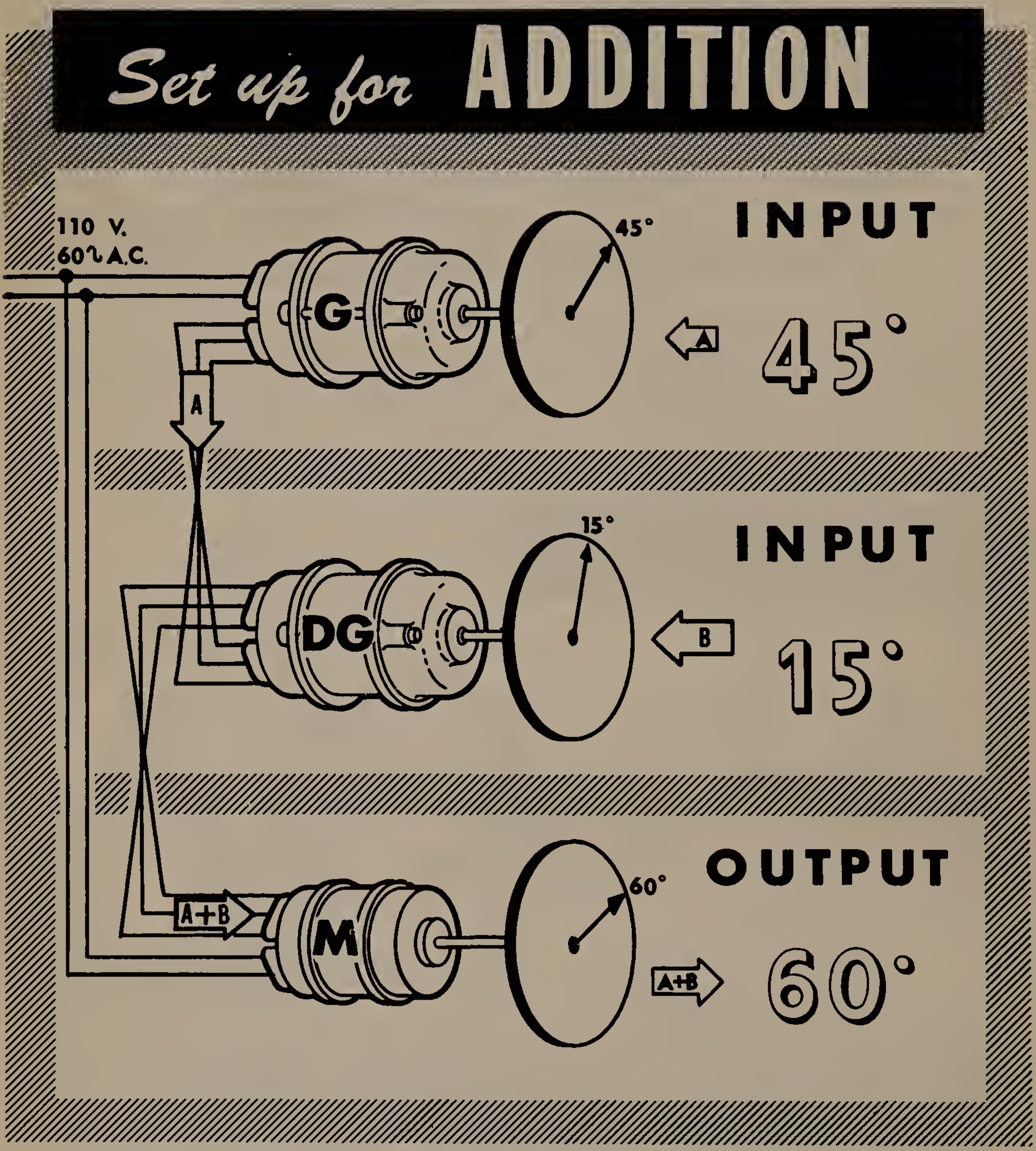


Notice that the rotor field of the DG is now at a 45-degree angle with respect to the S_2 axis, as a result of the 45-degree clockwise shift of the G rotor. Consequently the DG rotor field now lies parallel to the R_2 winding. The magnetic field in the stator of the motor must therefore be parallel to its S_2 winding. The rotor will line up with the stator field turning back from -45 degrees to zero degrees.

On the basis of the previous examples you can see that the motor shaft will take up a position which is the sum of the two inputs to the DG if they are in opposite directions—and the difference between the two inputs if they are in the same direction.

Differential Generator Addition

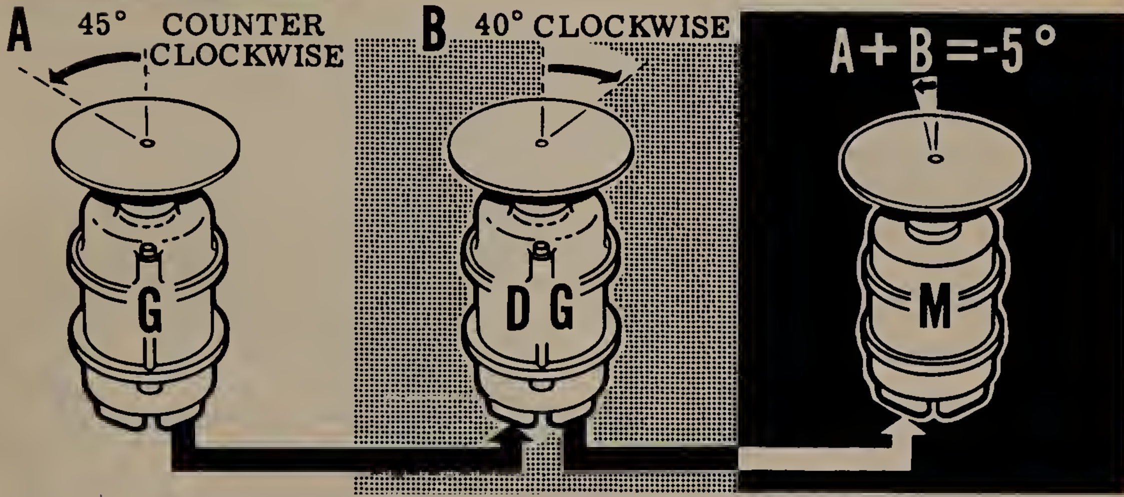
The diagram shows a three-piece synchro team consisting of a synchro generator, a synchro differential generator and a synchro motor set up for addition. The change from subtraction to addition is obtained by interchanging leads S_1, S_3 and R_1, R_3 as shown in the diagram. The shaft of the motor will turn to a position which is equal to the sum of the generator and differential shafts.



Notice that the signal which is transmitted to the synchro motor is the sum of electrical signal A and the mechanical signal B. The shaft of the synchro motor will position itself at an angle A + B.

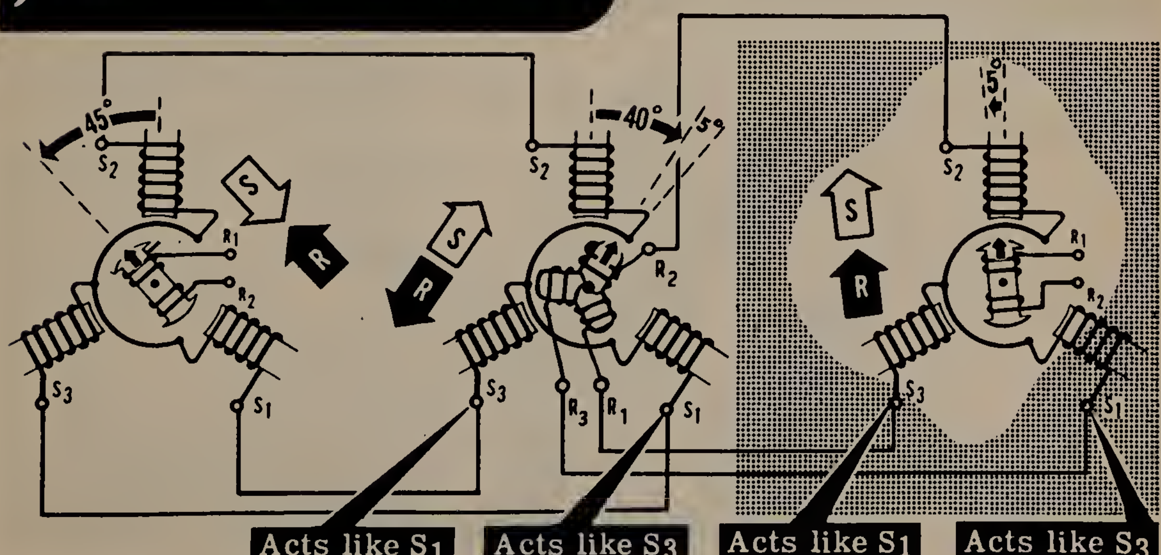
Differential Generator Addition (continued)

EXAMPLE NO. 1



In this problem the G is turned 45 degrees counterclockwise and the DG is turned 40 degrees clockwise. When the signal is transferred from the stator of the generator to the stator of the DG, it lies 45 degrees to the right of S_2. This can be explained by understanding that S_3 of the DG acts like an S_1 winding since it is connected to S_1 of the G, and S_1 of the DG acts like an S_3 winding since it is connected to S_3 of the G. The magnetic field in the stator of the G lies between S_2 and S_3 at a 45-degree angle to S_2 as shown. Therefore the magnetic field in the stator of the DG must also lie between S_2 and the equivalent S_3 at a 45-degree angle to S_2 as shown. The rotor field will lie parallel but opposite to the stator field. The position of the magnetic field relative to the rotor can be determined by referring to the illustration. The magnetic field lies 5 degrees to the right of R_2 and is pointing down. When the signal is transmitted to the motor, it will lie 5 degrees to the left of S_2 and point up. The rotor will line up with the stator field and will position itself 5 degrees to the left of S_2.

Follow it on the schematic

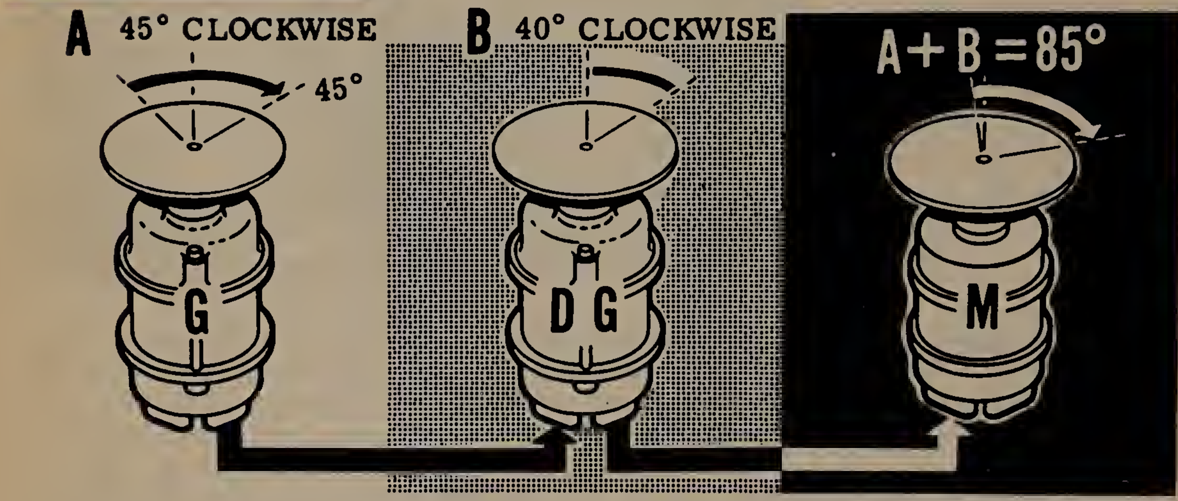


Differential Generator Addition (continued)

If the rotor of the DG is held at 40 degrees clockwise and the rotor of the generator is turned from -45 degrees to a final position of 45 degrees clockwise (a total of 90 degrees) the rotor of the motor will turn from -5 degrees to a final position of 85 degrees clockwise (a total of 90 degrees).

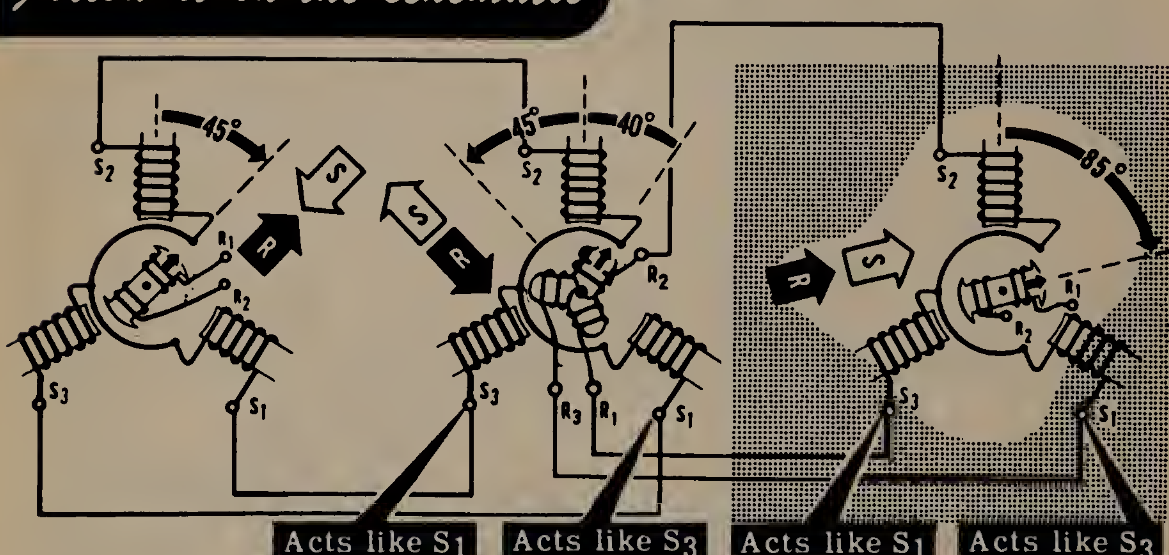
Example 2 is worked out below, using magnetic field analysis.

EXAMPLE NO. 2



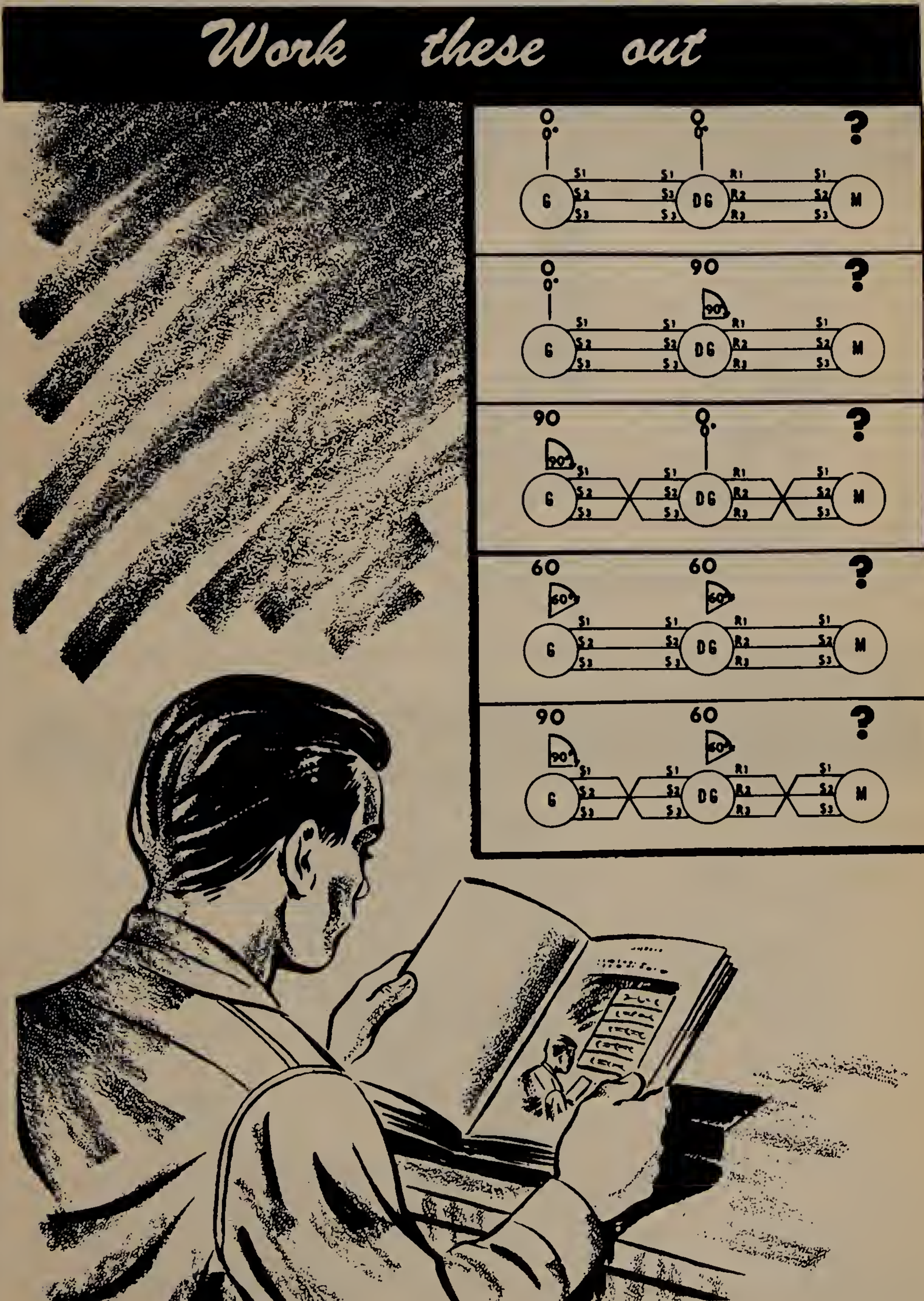
When the signal is transmitted from generator to the stator of the DG, it positions itself 45 degrees to the left of S_2. The position of the magnetic field relative to the rotor is 85 degrees to the left of R_2 with the arrow pointing down. When the signal is transferred from the rotor of the DG to the stator of the motor, it will be 85 degrees clockwise from S_2. The shaft of the motor will position itself at the same angle.

Follow it on the schematic



Problems

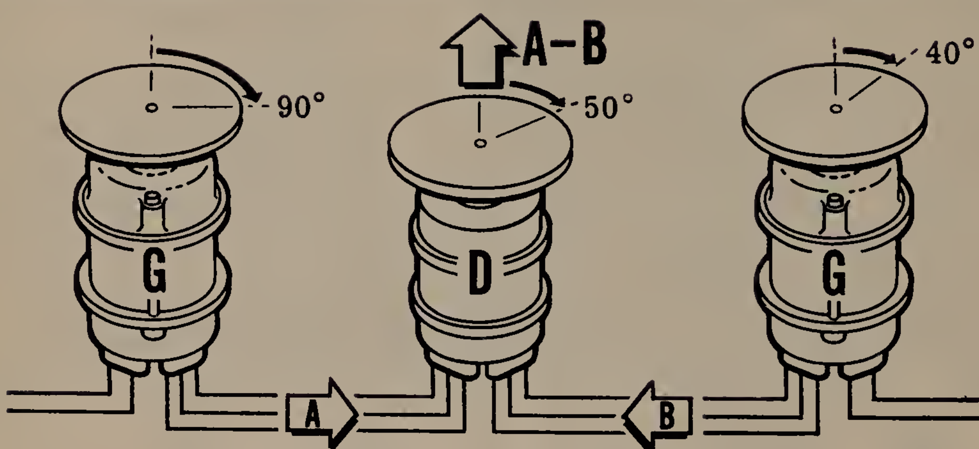
Now that you have analyzed the operation of a three-team synchro containing a DG, set up for either addition or subtraction, suppose you work out some problems—using the magnetic field analysis—to see if you can figure out what the final position of the motor shaft will be.



The Differential Motor

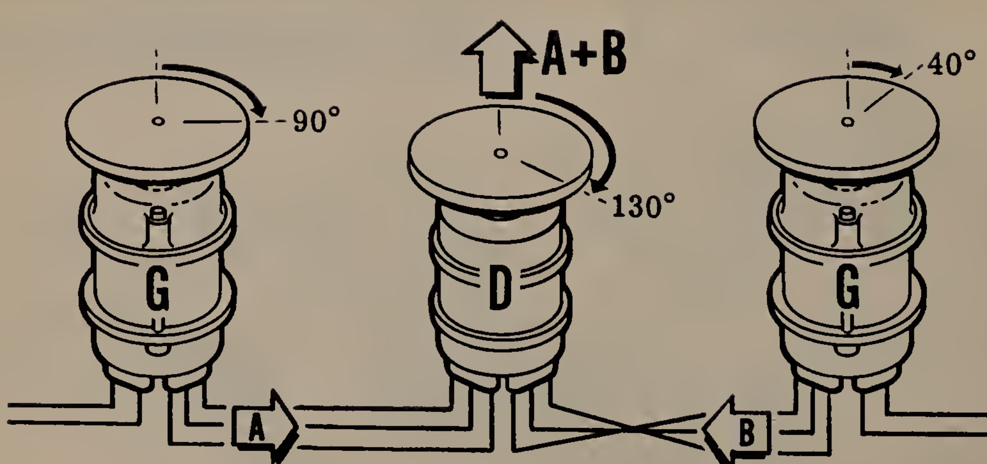
As previously explained, the differential motor is a DG with a damper to prevent oscillation and spin. The differential motor is used to indicate either the sum or difference between two inputs. The usual set-up is to have two synchro generators feeding signals into the differential motor. The shaft will then position itself to either the sum or difference of the two signal inputs as shown. For subtraction, the stators and rotors are connected as shown.

...set up for SUBTRACTION...



For differential motor addition, the motor leads S_1, S_3 and R_1, R_3 are reversed as shown.

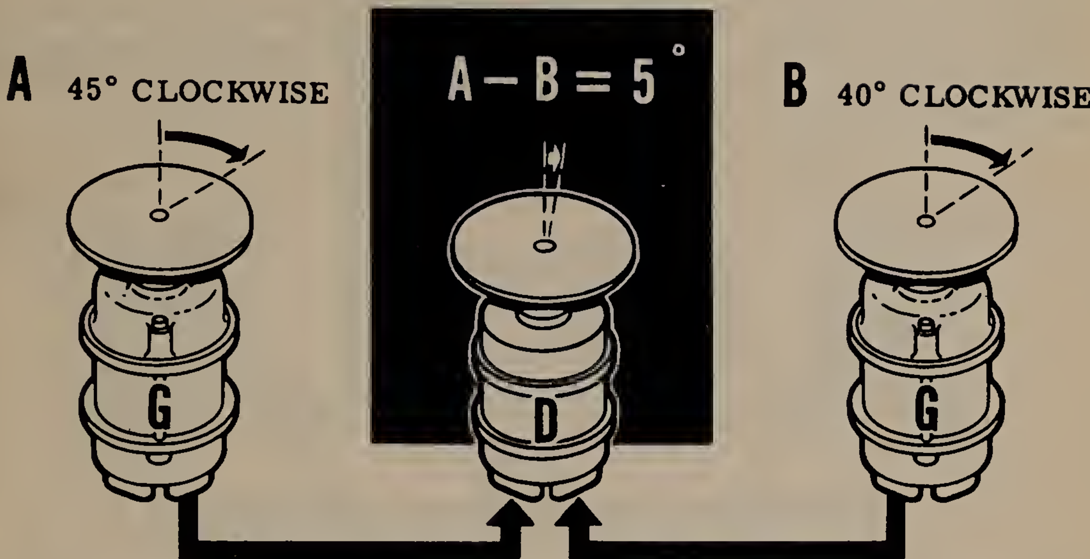
...set up for ADDITION...



Two problems will clarify for you the operation of the three-team synchro using a differential motor.

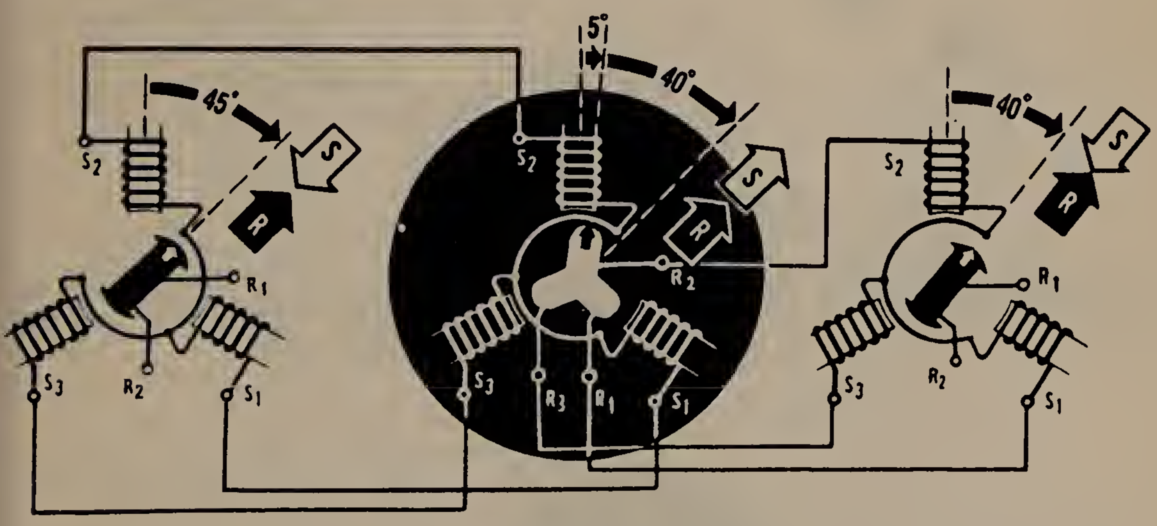
Differential Motor Subtraction

Example of Subtraction:



If the rotor of one G is turned to 45 degrees and the rotor of the other G is turned to 40 degrees, the rotor of the motor will position itself to 5 degrees—the difference between the two signals.

The example of subtraction is worked out below, using magnetic field analysis.

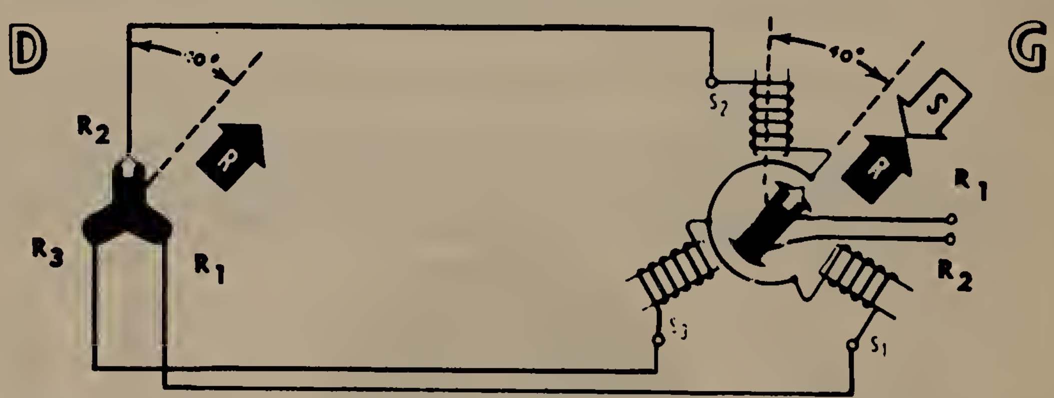


The motor shaft will so position itself that its magnetic field will line up with the stator magnetic field. The stator magnetic field lies at an angle of 45 degrees clockwise from S_2. The rotor magnetic field lies at an angle of 40 degrees clockwise from R_2. The rotor shaft will turn until the magnetic fields line up. Winding R_2 will then be 5 degrees clockwise from S_2 and the dial reading will be 5 degrees. A detailed analysis of this problem is presented on the following sheet.

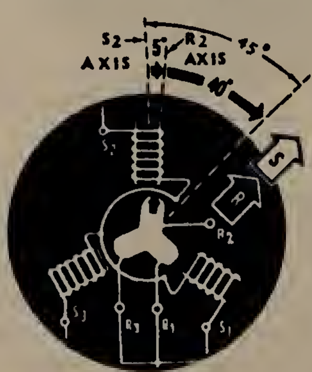
Differential Motor Subtraction (continued)

When the rotor of the G on the left is positioned at 45 degrees, it will cause a magnetic field to be induced in the stator of the D which will also be positioned at 45 degrees as shown. This stator magnetic field will attract the magnetic field in the rotor of the D, causing the rotor to turn until the two magnetic fields line up. Therefore, if you know the angular position of the rotor field relative to its R_2 winding, you can tell what the final position of the rotor of the D will be.

The rotor of the other G is positioned at 40 degrees. Therefore it will induce a magnetic field in the rotor of the D which will also be positioned at 40 degrees relative to its R_2 winding as shown.

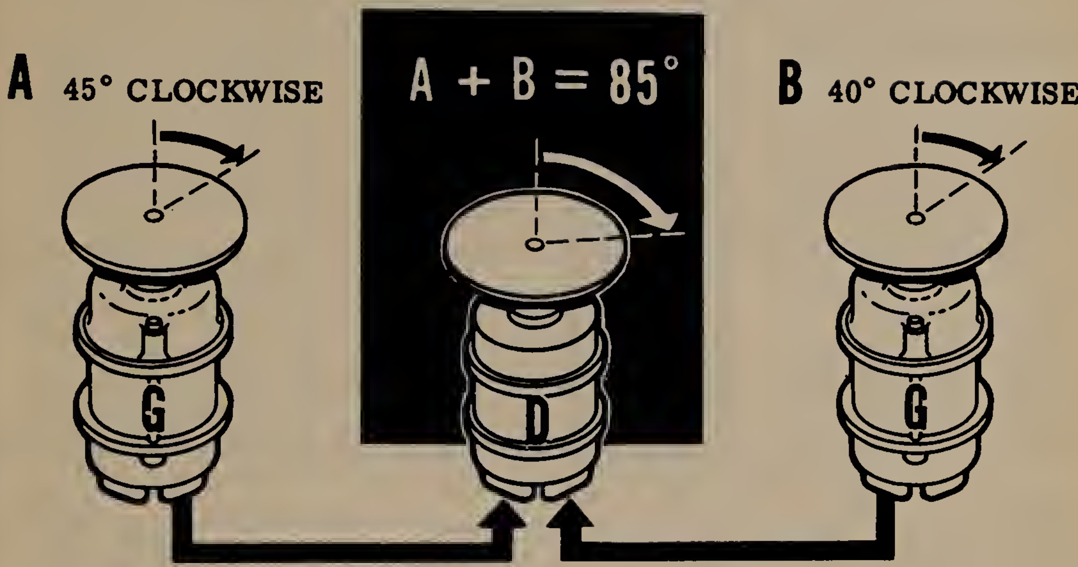


The magnetic field in the rotor of the D will be attracted by the stator magnetic field and will line up with it as shown. The resulting angular displacement of R_2 relative to S_2 must be 5 degrees as illustrated.



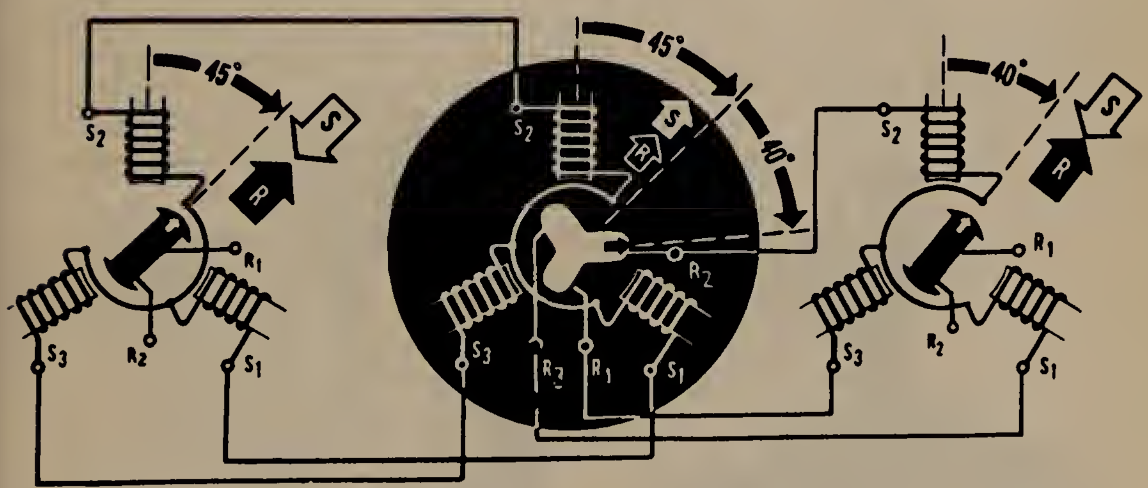
Differential Motor Addition

Example of addition:



If the rotor of one G is turned to 45 degrees and the rotor of the other G is turned to 40 degrees, the rotor of the motor will position itself to 85 degrees—the sum of the two signals.

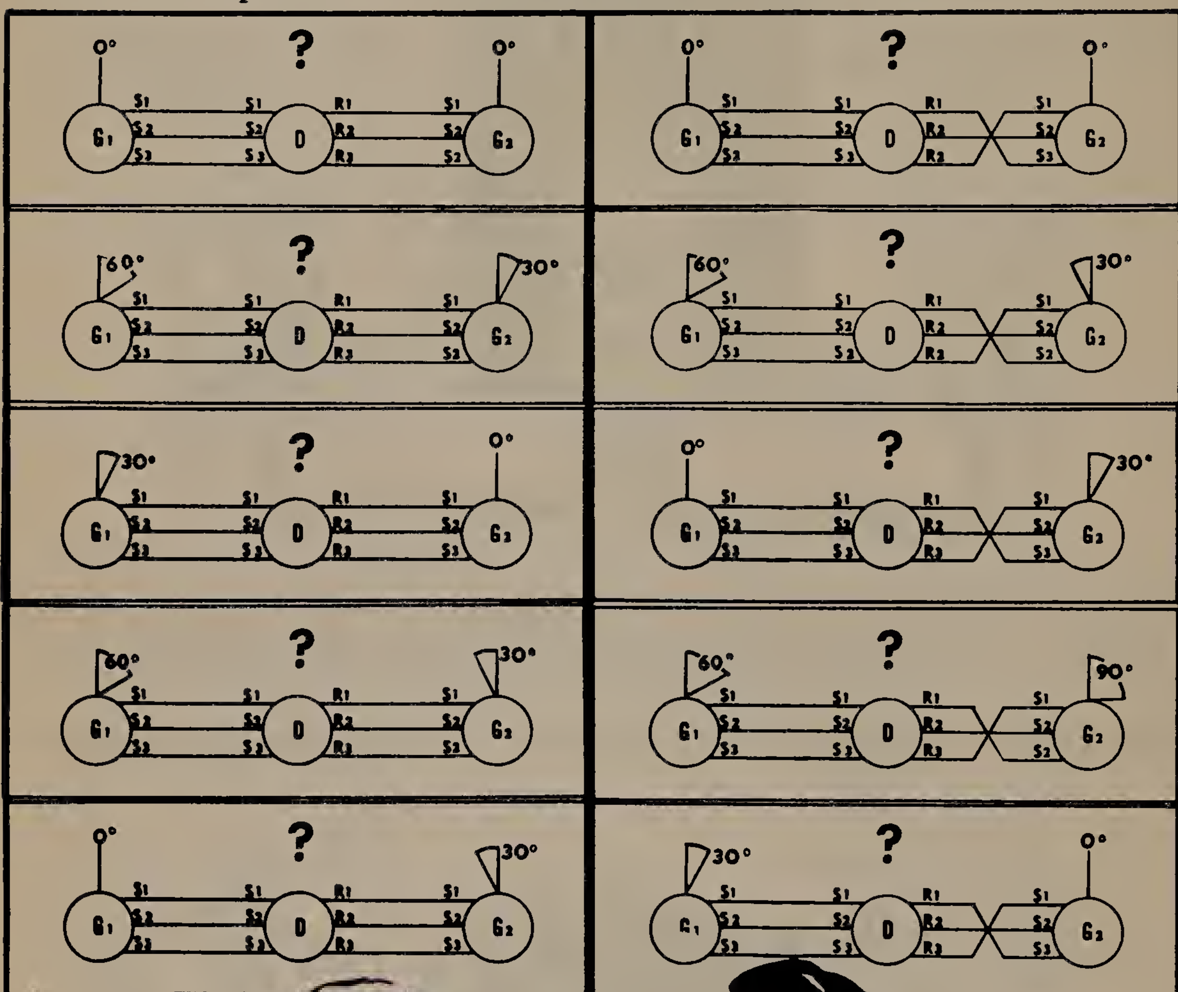
The example of addition is worked out below, using magnetic field analysis.



The motor shaft will so position itself that the rotor field will line up with the stator field. The stator magnetic field lies at an angle of 45 degrees clockwise from S_2. The rotor magnetic field lies now at an angle of 40 degrees counterclockwise from R_2. The rotor shaft will turn until the magnetic fields line up. Winding R_2 will then lie 85 degrees clockwise from S_2 as shown.

Problems

You will now have a chance to work out some problems on the operation of a three-team synchro containing a differential motor set up for either addition or subtraction. Using the magnetic field analysis, figure out what the final position of the differential motor shaft will be.

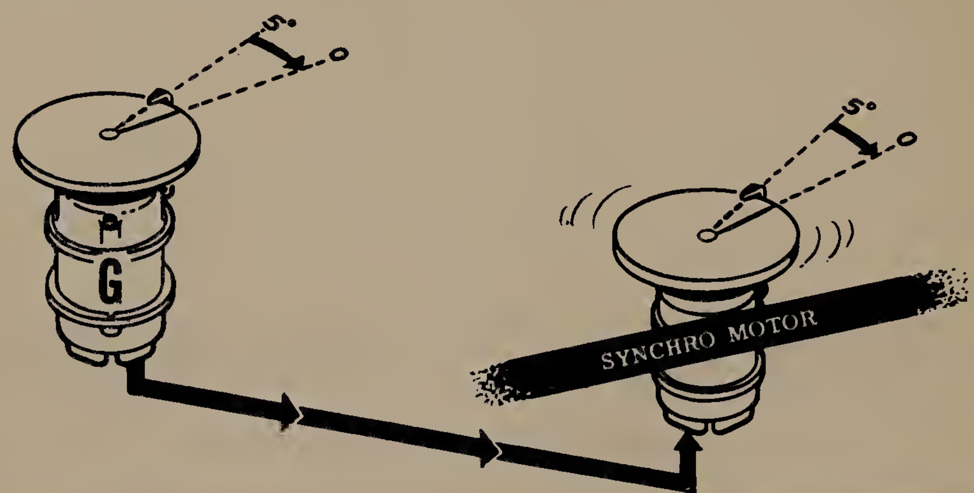


Having worked out the above problems, you have completed your study of the synchro differential. You will next learn about the last member of the synchro family, the control transformer.

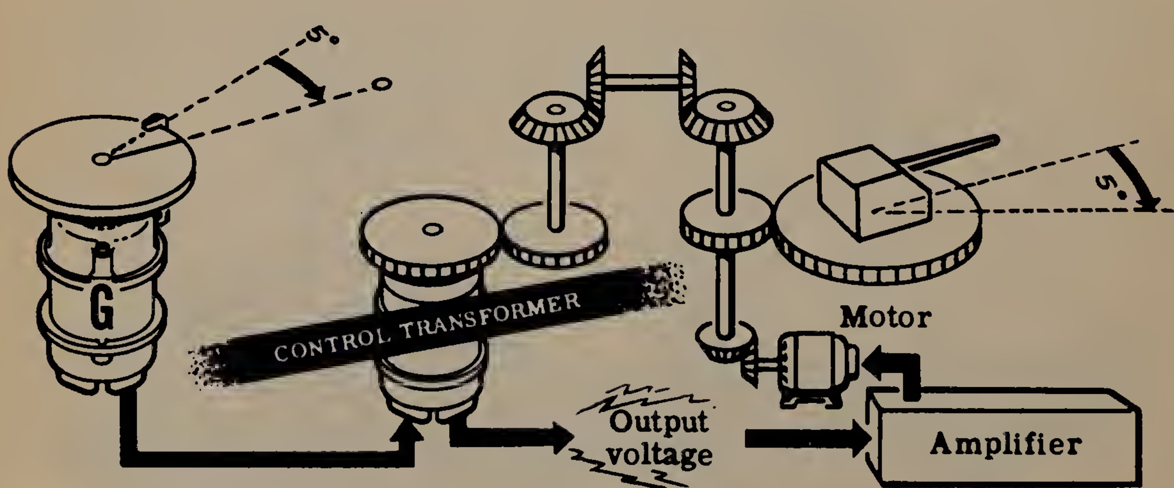
THE CONTROL TRANSFORMER

General Information

The control transformer can be compared to the synchro motor for purposes of explanation. Both receive an electrical signal input to their stators. The signal may come either from a generator or a DG. However, the motor and the control transformer differ in their outputs. The output of the synchro motor is a mechanical positioning of its shaft. The output of the control transformer is a voltage which is induced in the rotor winding. This voltage is used to control the action of a power drive system which can position a heavy mechanism.



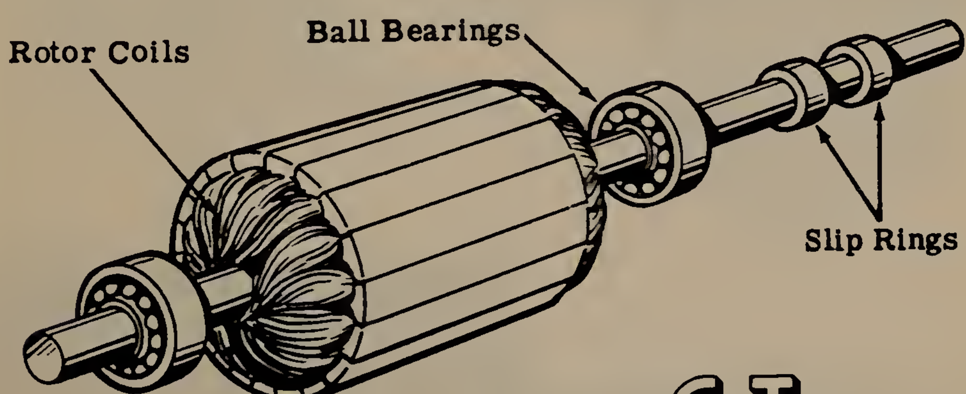
SYNCHRO MOTOR OUTPUT IS A MECHANICAL POSITIONING

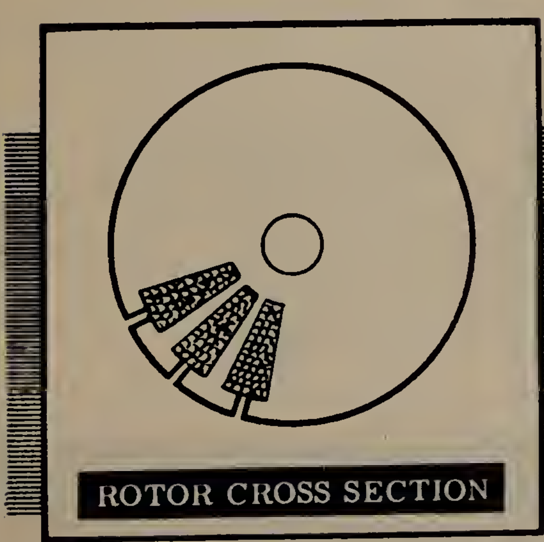


CONTROL TRANSFORMER OUTPUT IS AN ELECTRICAL VOLTAGE

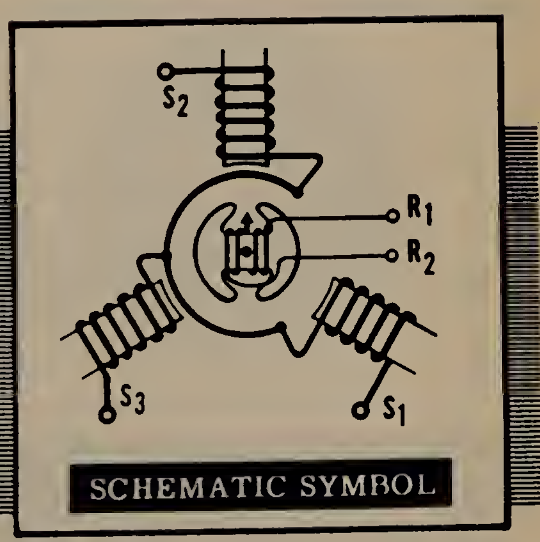
The Control Transformer Construction

The stator of the control transformer is very similar to stators of other synchros with one exception—the windings are made of many more turns of finer wire. The reason for the increased number of turns is to make the impedance of the stator high. The need for a high impedance is to limit the flow of current through the stator. The rotor of the control transformer is one series winding just like the rotor of the generator or motor. However, its shape is completely round, not bobbin-shaped as in the synchro motor. The round shape prevents the rotor from being attracted by the magnetic field in the stator. As a result, the rotor will not turn to any particular position as the magnetic field in the stator shifts position. The only torque exerted on the rotor shaft will be due to the mechanical coupling of the shaft to a driving motor.





ROTOR CROSS SECTION

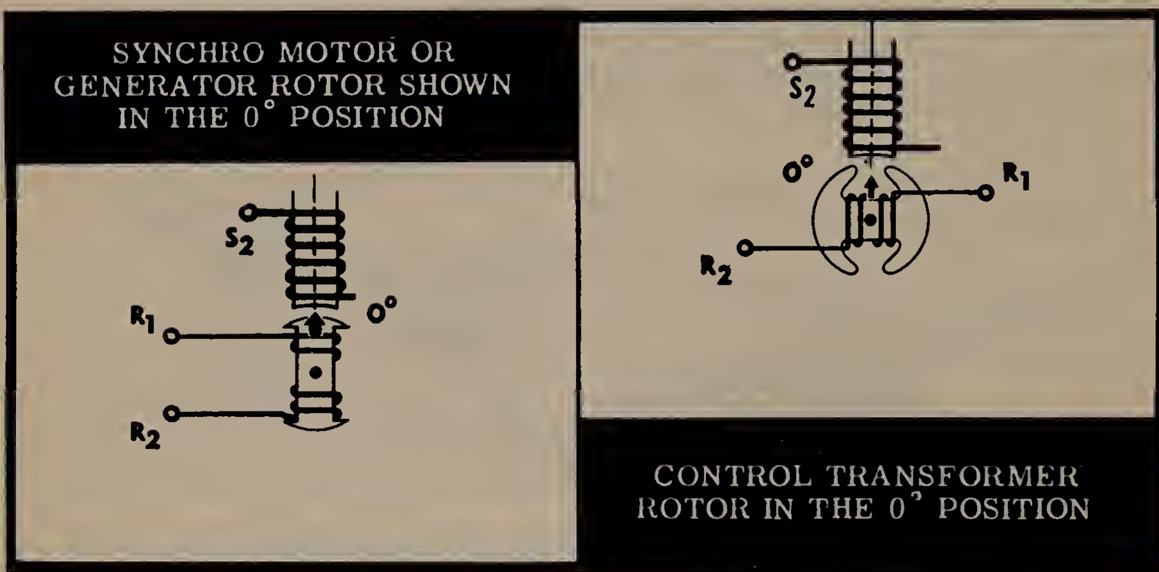


SCHEMATIC SYMBOL

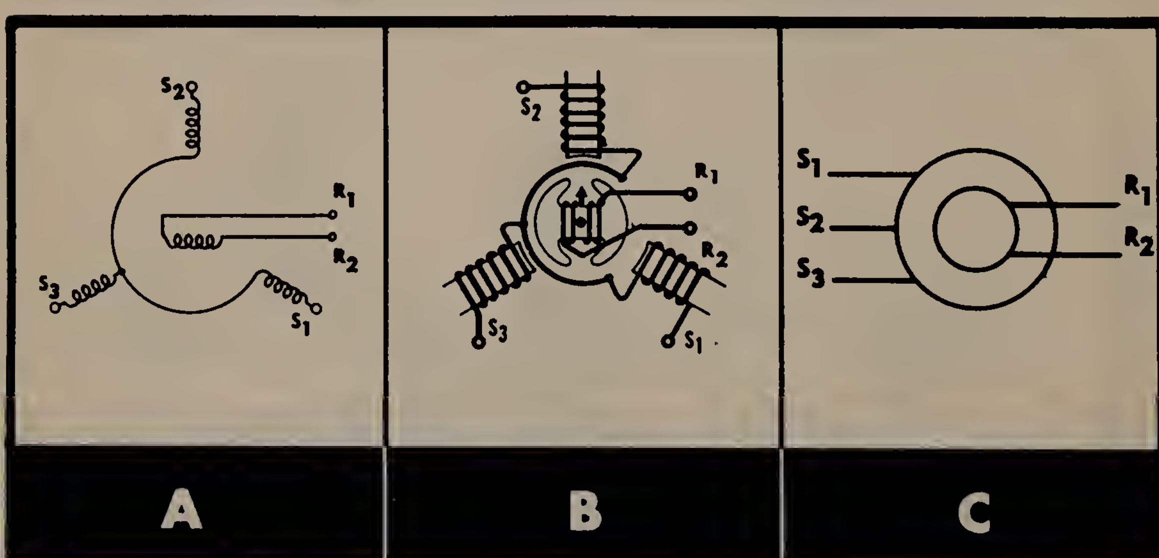
The ends of the rotor winding are connected to slip rings on the shaft. Brushes bear against these slip rings and bring out the signal on two leads labeled R_1 and R_2.

The Control Transformer Schematic

The illustration shows the electrical zero position of a synchro generator and motor as well as the electrical zero position of a control transformer. A synchro generator or motor is zero-positioned when its rotor lines up with the S_2 winding as shown. A control transformer is zero-positioned when the voltage induced in the rotor by the S_2 winding is a minimum. This is when the rotor lies at right angles to the direction of the magnetic field in the S_2 winding as shown.



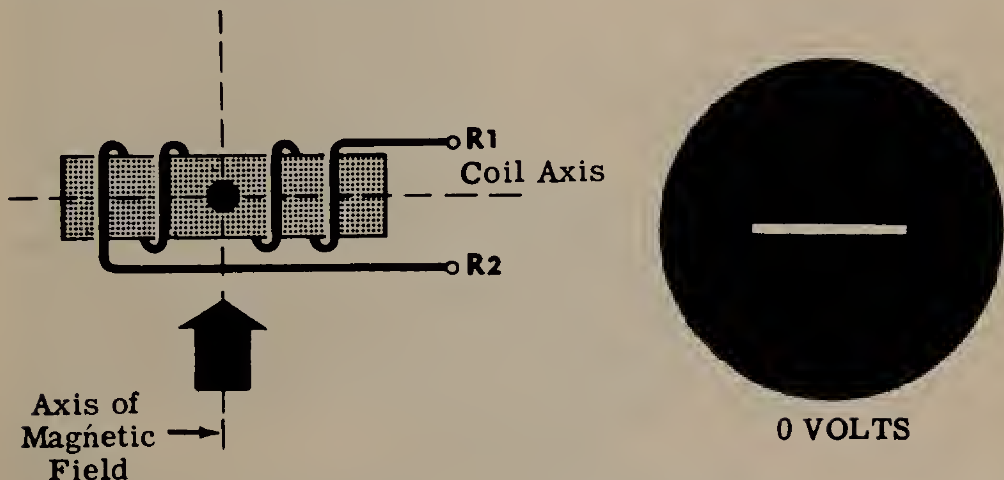
The next diagram shows the three types of control transformer schematics that you will come across both in this book as well as in other books.



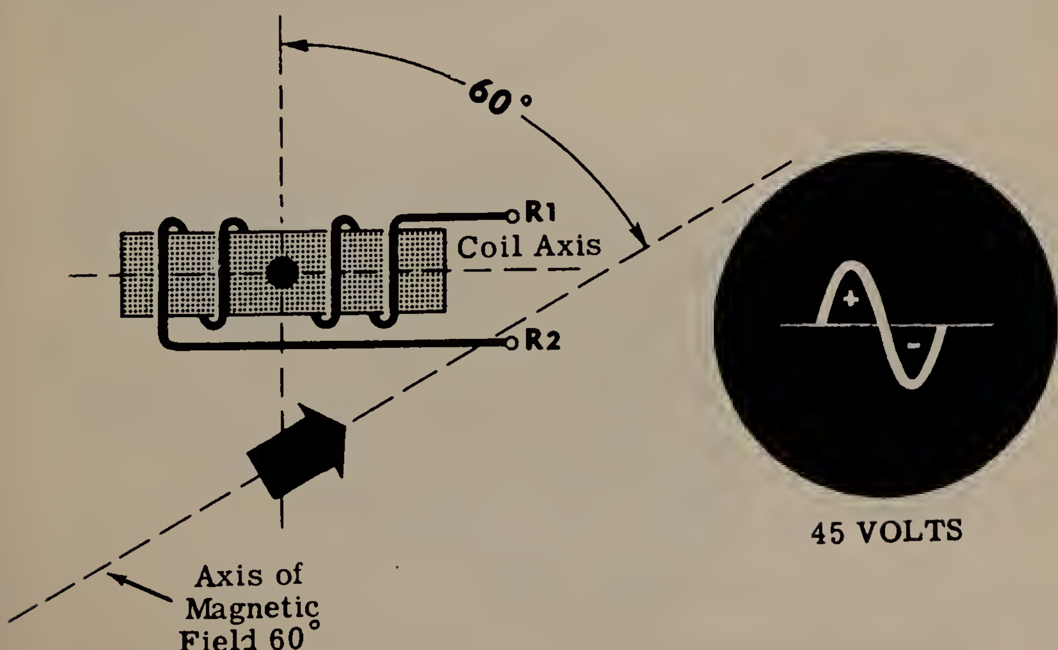
Schematic A is the standard symbol used in prints. Schematic B is used when explaining the operation of the control transformer. Schematic C is a frequently used simplified diagram.

Simple Transformer Theory

In order to help you understand how the control transformer works, you are going to analyze a simple transformer action. The diagram shows a pivoted coil in a horizontal position at right angles to an alternating magnetic field. Just as we have done previously, the magnetic field is represented by an arrow. Since the coil is at right angles to the field, there is no coupling between the magnetic field and the turns of the coil. The voltage induced in the coil will be zero, and an oscilloscope placed across R_1-R_2 will show a straight line.



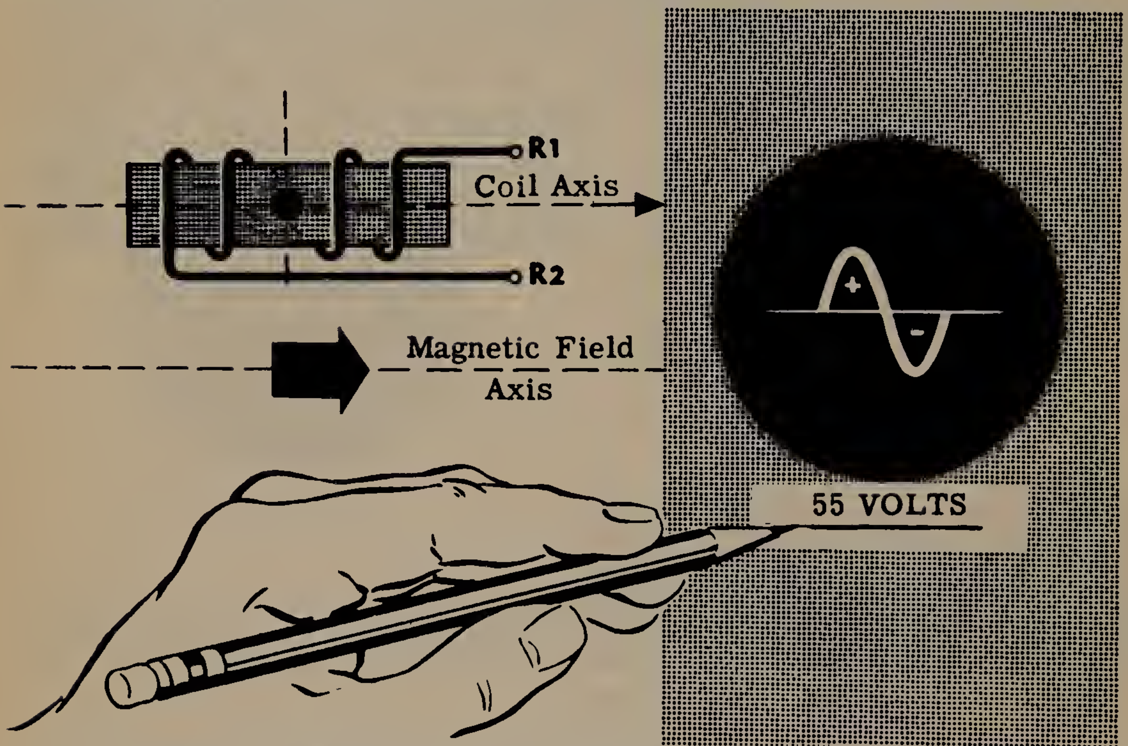
If the magnetic field is made to rotate 60 degrees clockwise as shown, there will be some coupling between the magnetic field and the coil. As a result, a voltage will be induced in the coil (assume it to be 45 volts), and a sine wave will be seen on the 'scope.



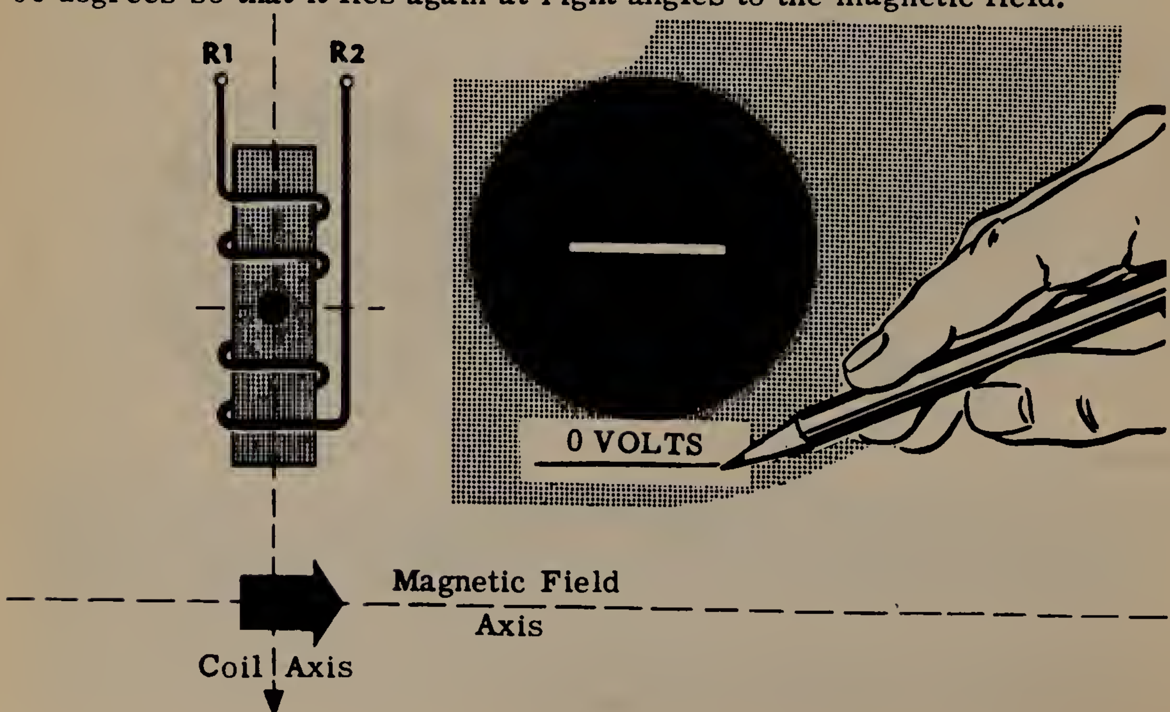
If it is desired to bring the induced voltage back to zero, all that has to be done is to turn the coil 60 degrees clockwise so that it once more lies at right angles to the inducing magnetic field.

Simple Transformer Theory (continued)

If the magnetic field is made to rotate 90 degrees clockwise as shown, maximum coupling exists between the magnetic field and the coil. As a result, a maximum voltage of 55 volts will be induced in the coil. Since the magnetic field cuts through the coil in the same direction as it did at 60 degrees, the wave form at 90 degrees will be in phase with the wave form at 60 degrees. The 'scope picture shows this.

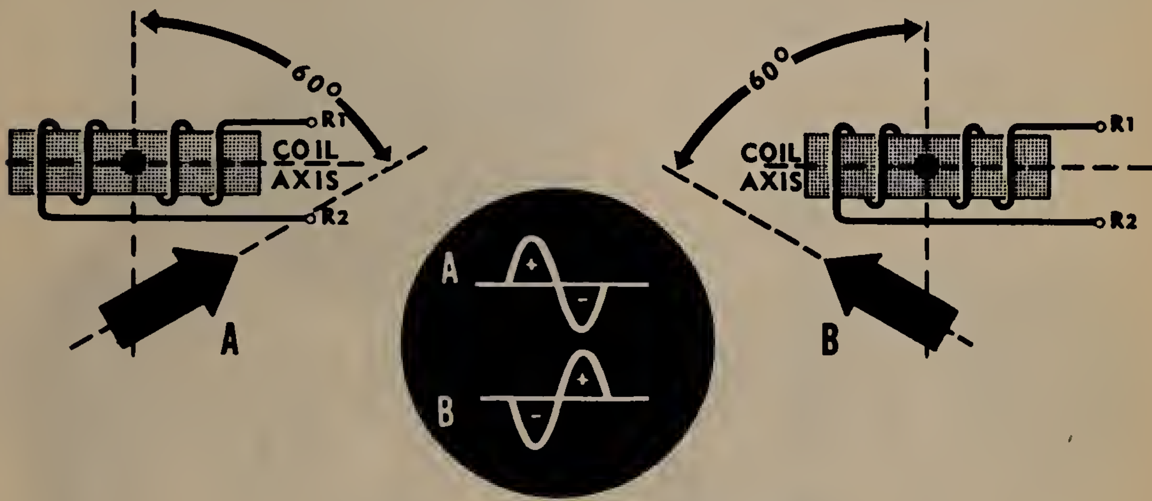


You can again bring the induced voltage back to zero by turning the coil 90 degrees so that it lies again at right angles to the magnetic field.



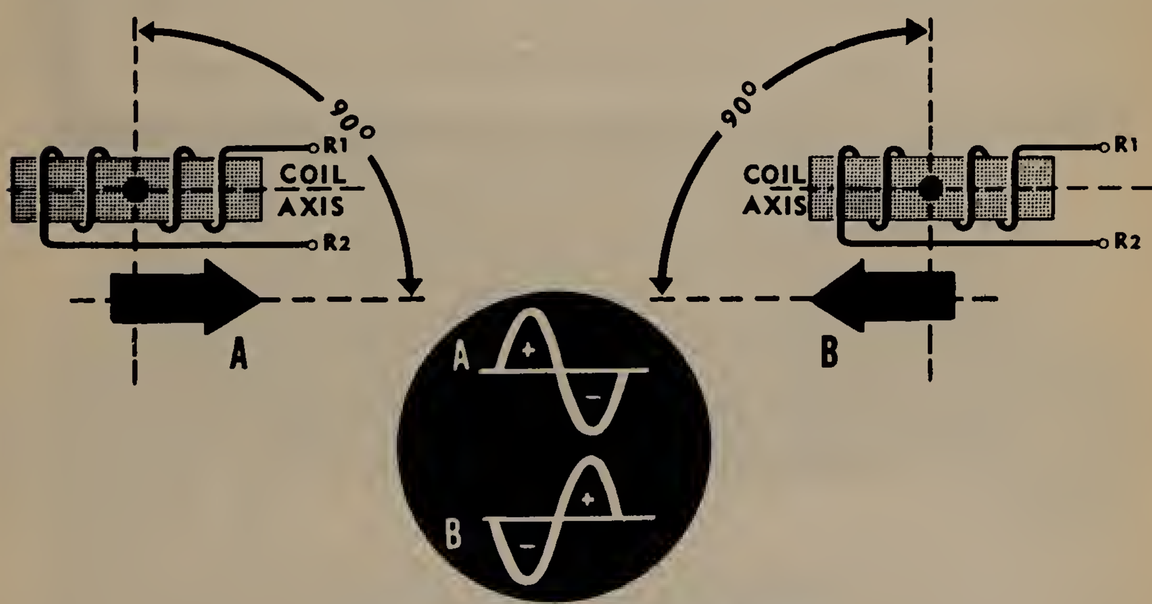
Simple Transformer

Suppose you start from the beginning again and this time rotate the inducing magnetic field 60 degrees counterclockwise (B). The voltage induced in the coil will be the same as it was before at 60 degrees clockwise (A), only this time the polarity of the wave form is reversed. The reason for the 180-degree change in phase is because now the magnetic field is cutting through the coil in the opposite direction to what it was before.



OUT OF PHASE

The same reasoning holds true when the magnetic field is rotated counterclockwise to 90 degrees. Here again the induced voltage will be equal but out of phase with the induced voltage at the 90-degree clockwise position.



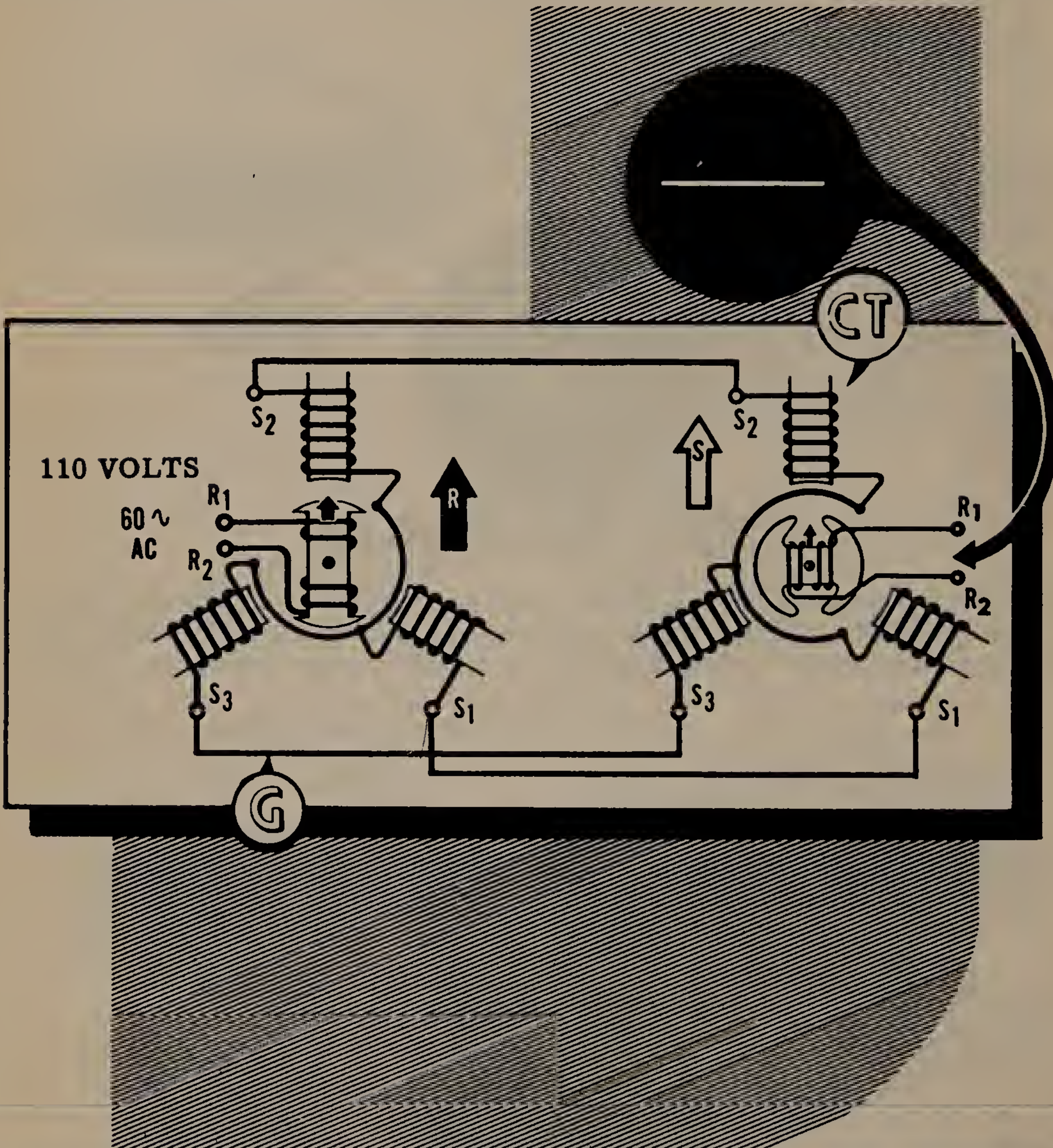
OUT OF PHASE

The induced voltage can always be brought back to zero by rotating the coil so that it lies at right angles to the magnetic field.

How the Control Transformer Works

Suppose you utilize the information you just gained to help you understand the operation of a control transformer.

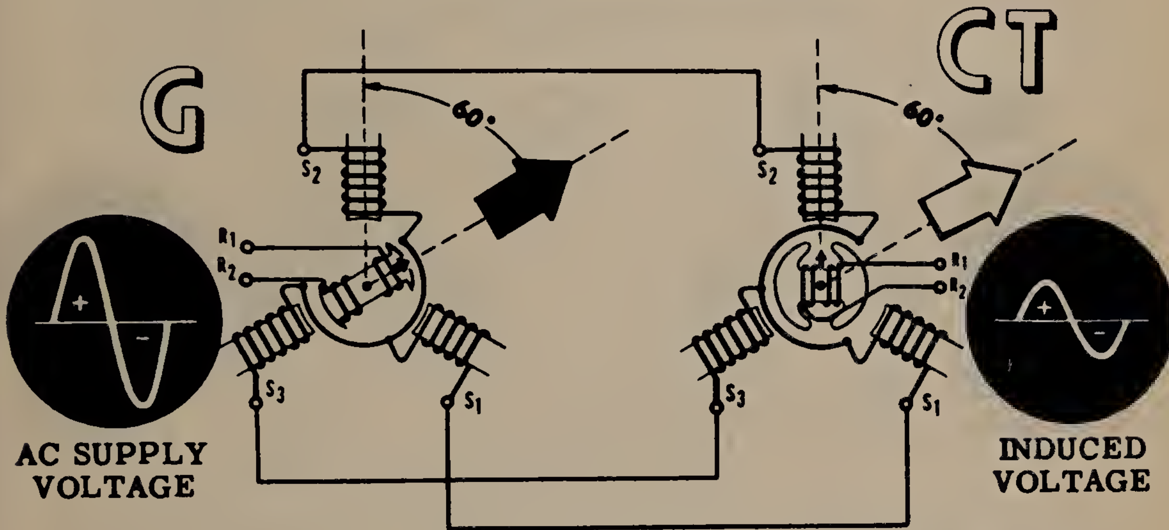
You will consider the operation of a synchro generator-control transformer team. The diagram shows the stator of a generator hooked up to the stator of a control transformer. Both synchros are shown on electrical zero.



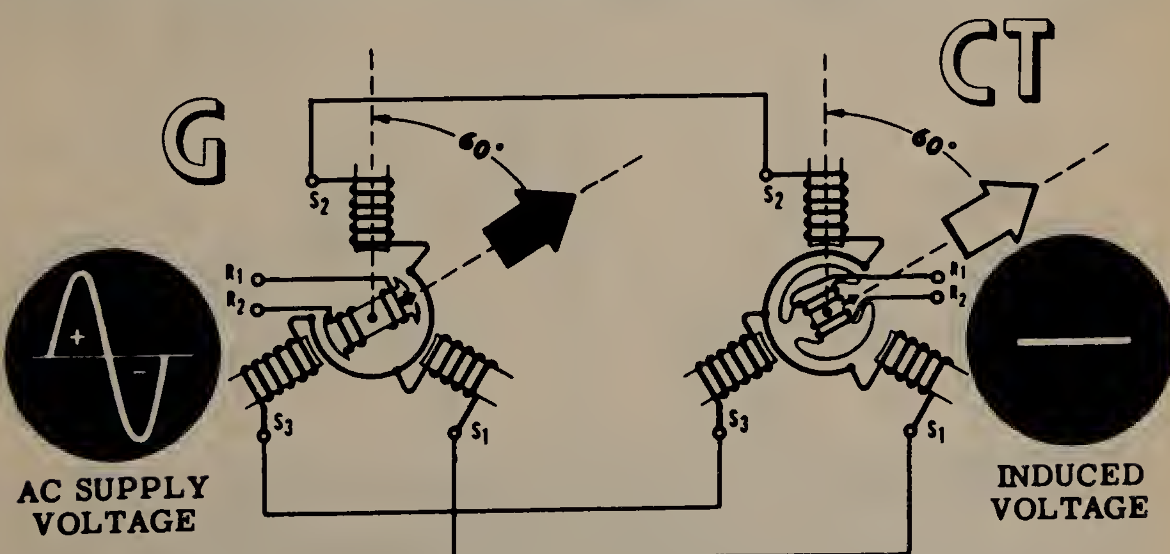
When the rotor of the generator is in the zero position, the rotor magnetic field points straight up as shown. The magnetic field in the stator of the control transformer will always parallel the rotor field and, therefore, will also point straight up. Observe that the rotor of the control transformer lies at right angles to the stator magnetic field and, therefore, the induced voltage in the rotor is zero.

How the Control Transformer Works (continued)

When the rotor of the generator is turned 60 degrees clockwise, the magnetic field in the generator and the control transformer also rotate 60 degrees clockwise, and a voltage is set up across the rotor terminals R_1-R_2. The rotor of the control transformer is so wound, that a clockwise rotation of the magnetic field induces a voltage across the transformer leads R_1-R_2 which is in phase with the AC supply to the generator rotor as shown. As the rotor of the generator turns from zero degrees to 90 degrees, the induced voltage across the rotor of the control transformer increases from zero until it reaches its maximum value at 90 degrees.

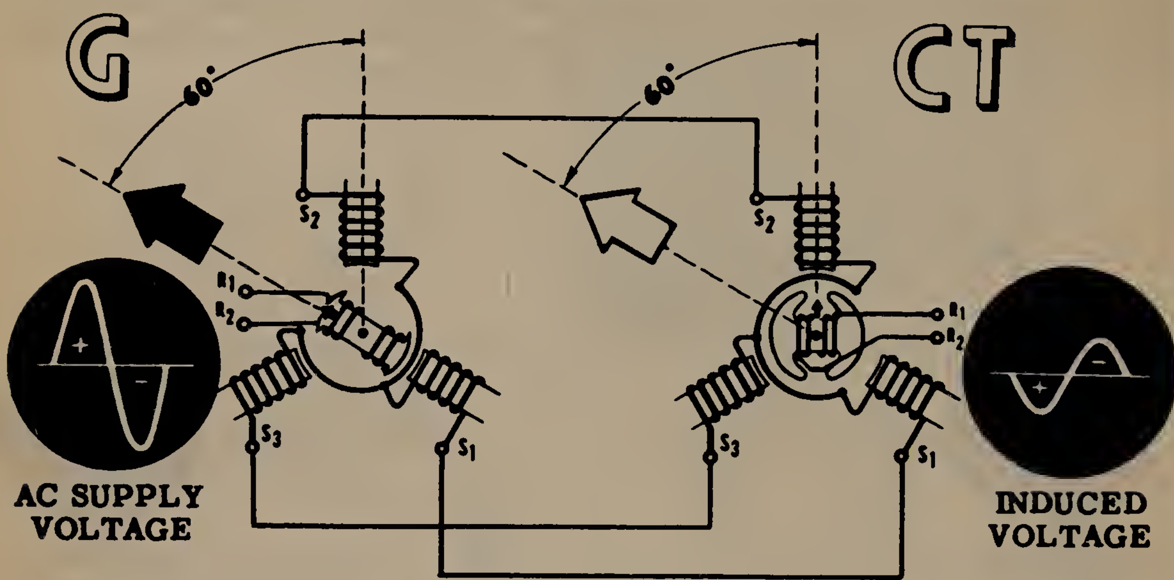


The induced voltage across the rotor of the control transformer can be brought to zero by turning the control transformer rotor through the same number of degrees and in the same direction as the rotor of the generator.

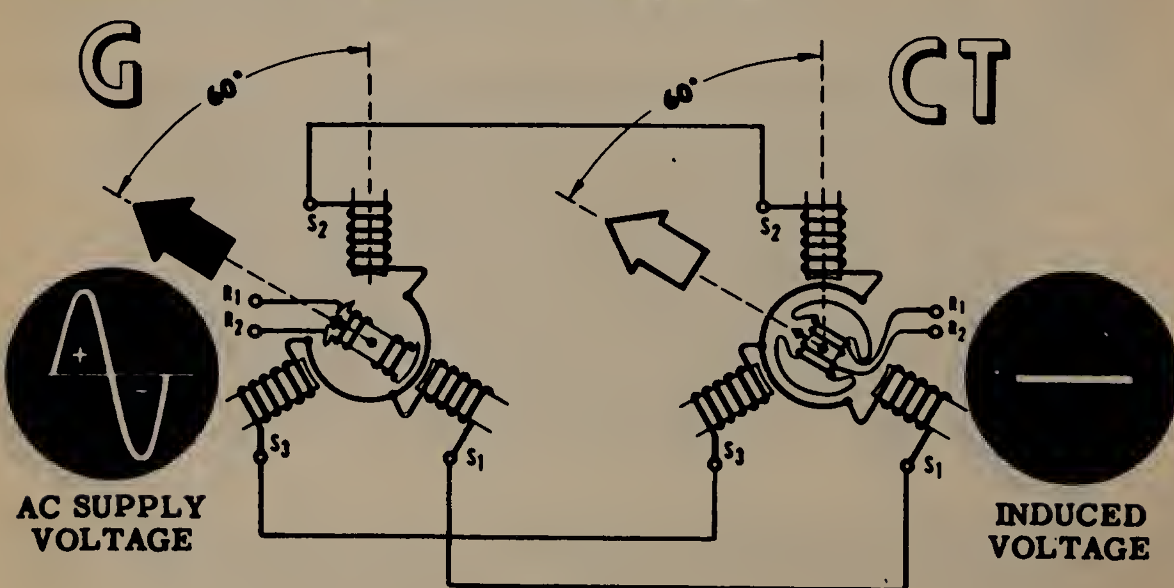


How the Control Transformer Works (continued)

If the rotor of the generator is turned in a counterclockwise direction from its zero position, the magnetic field in the CT will also rotate counterclockwise through the same number of degrees as the generator shaft. Since the magnetic field in the stator of the CT now cuts through the rotor in the opposite direction, the induced voltage in the rotor will now be out of phase with the AC supply to the generator as shown.



The induced voltage across the rotor of the CT can again be brought back to zero by turning the CT rotor through the same number of degrees and in the same direction as the rotor of the generator.

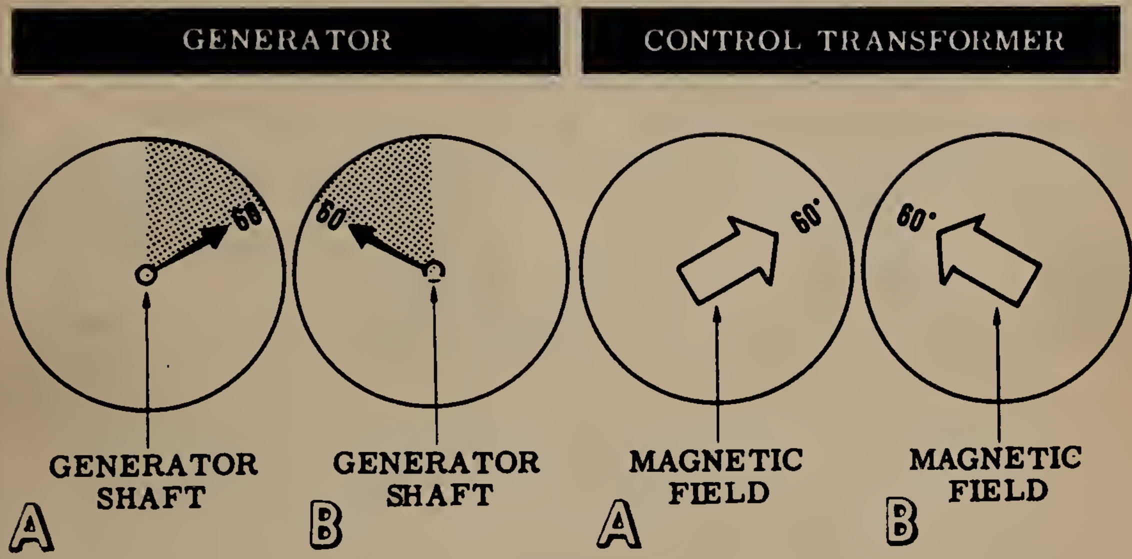


Summarizing Control Transformer Action

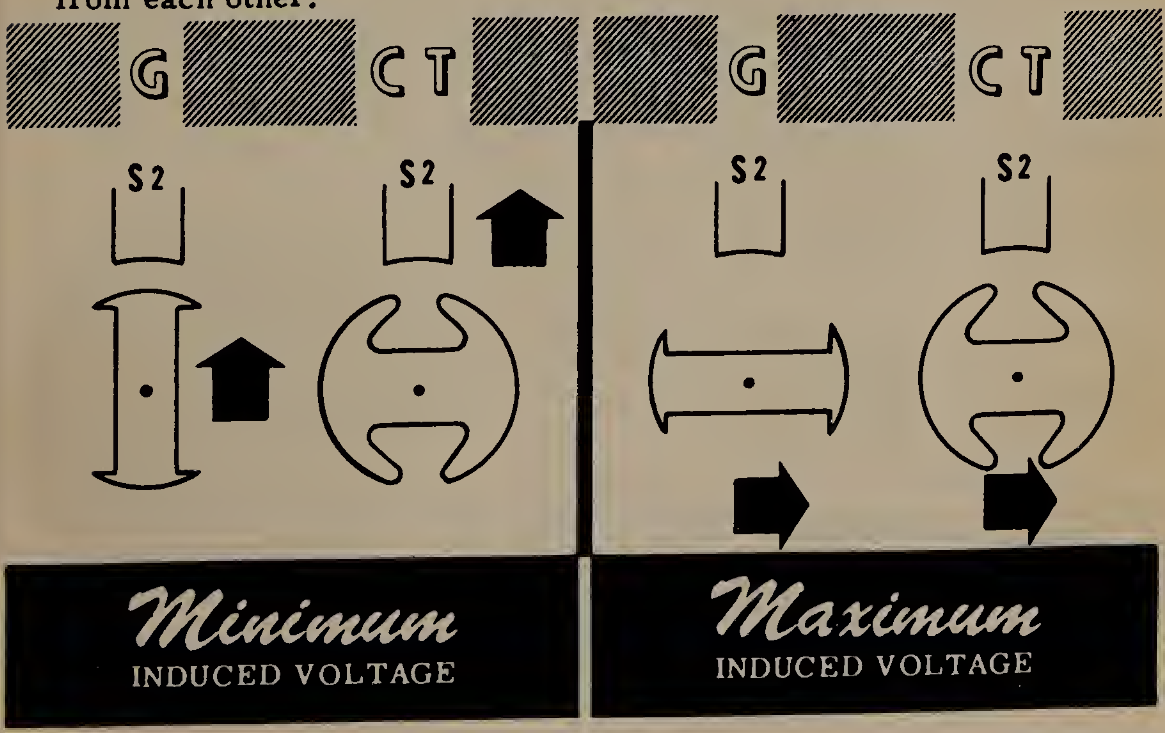
Following is a summary of the action of the control transformer:

When the rotor of the generator is turned, the following action takes place:

1. The magnetic field in the control transformer rotates in the same direction and by the same amount as the generator shaft.

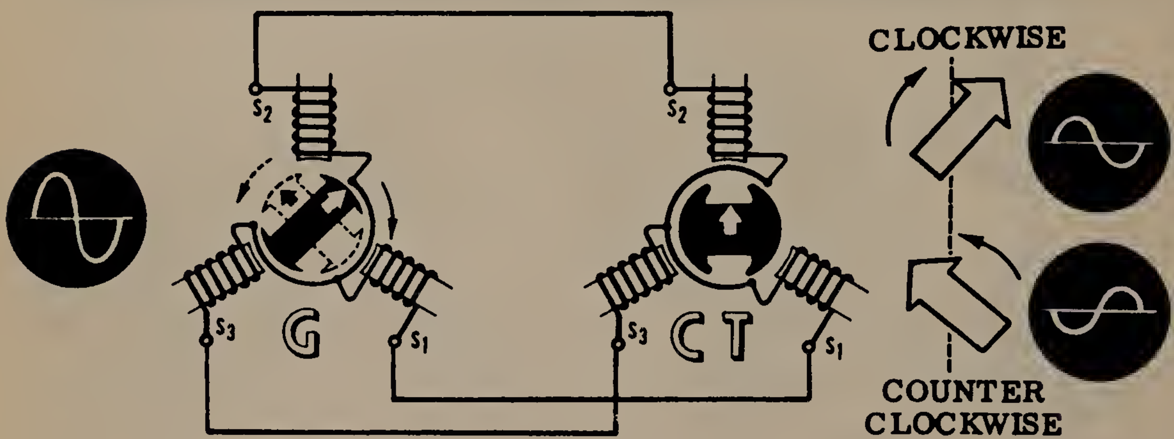


2. The transformer field induces a voltage in the rotor. This voltage is at a minimum when the field and rotor are at right angles. It is at a maximum when the field and rotor are in line. The strength of the CT voltage output indicates the amount the G and CT rotors are displaced from each other.

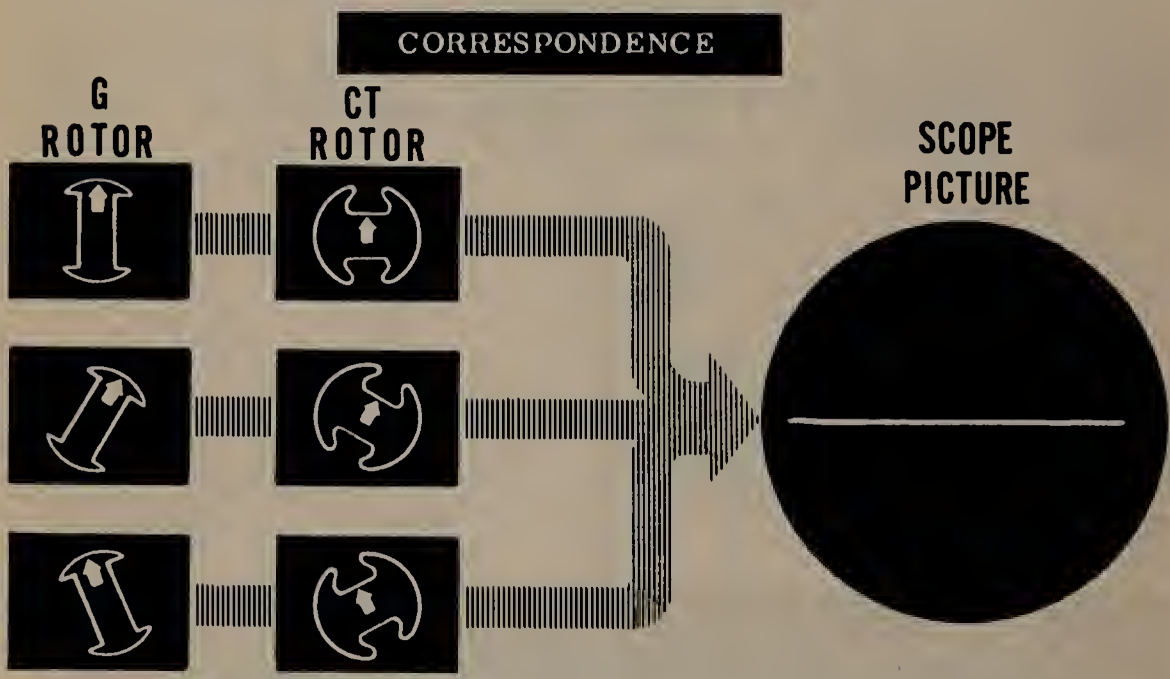


Summarizing Control Transformer Action (continued)

3. The polarity of the control transformer's output voltage is either in phase or out of phase with the voltage applied to the generator rotor. The voltage is in phase when the magnetic field is positioned clockwise from the CT rotor. The voltage is out of phase when the magnetic field is positioned counterclockwise from the CT rotor. In other words, the phase of the CT output reverses as the direction of displacement of the generator reverses. Another way of saying it is that the phase of the CT output indicates the signal direction.



4. The control transformer's output voltage can be brought to zero by rotating the CT rotor through the same angular displacement and in the same direction as the generator shaft. The CT rotor then lies at right angles to the magnetic field. When the CT rotor is turned to a position where its output drops to zero, it is said to be in correspondence with the generator rotor.



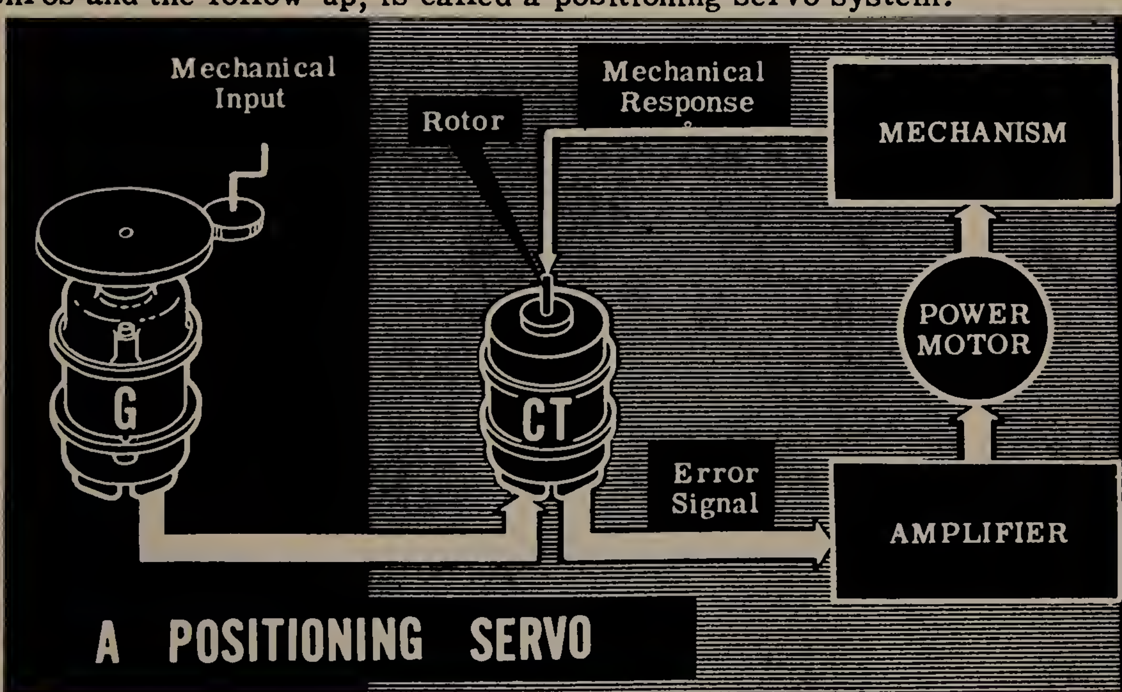
Now that you know how a control transformer works, you will see how it is used in a practical application.

How the Control Transformer Is Used

Synchros find extensive application in remote control positioning systems. For example, in the introduction to this book you read about a system which is used to remotely position a sonar transducer. In this system the operator turned a dial through a certain number of degrees and the transducer at the other end of the system turned through the same number of degrees at almost the same time.
A synchro system consisting of a synchro generator-motor team is not able to position the transducer because the motor is incapable of producing a strong enough torque. The way to overcome the limitations of the motor is to replace it with a control transformer and a follow-up.

The function of the CT is to produce an output voltage called an "error" signal. This name means the strength and phase of the voltage represents the amount and direction that the G and CT rotors are out of correspondence with one another. The function of the follow-up is to convert the error signal into the power necessary to drive a mechanism such as a transducer. While the follow-up is turning the mechanism it is also turning the CT rotor, through a mechanical linkage called a "response," in such a direction as to decrease the error signal. When the response turns the CT rotor so that it is once again in correspondence with the rotor of the generator, the error signal drops to zero and the system comes to a stop. The beauty of the above system is that the instant the shaft of the generator rotor is turned ever so slightly, a small error signal will be generated across the CT rotor and this small error signal will immediately be converted into power to drive the mechanism.

The illustration shows a block-diagram of a simple CT follow-up system for positioning a mechanism. The entire system, consisting of the synchros and the follow-up, is called a positioning servo system.

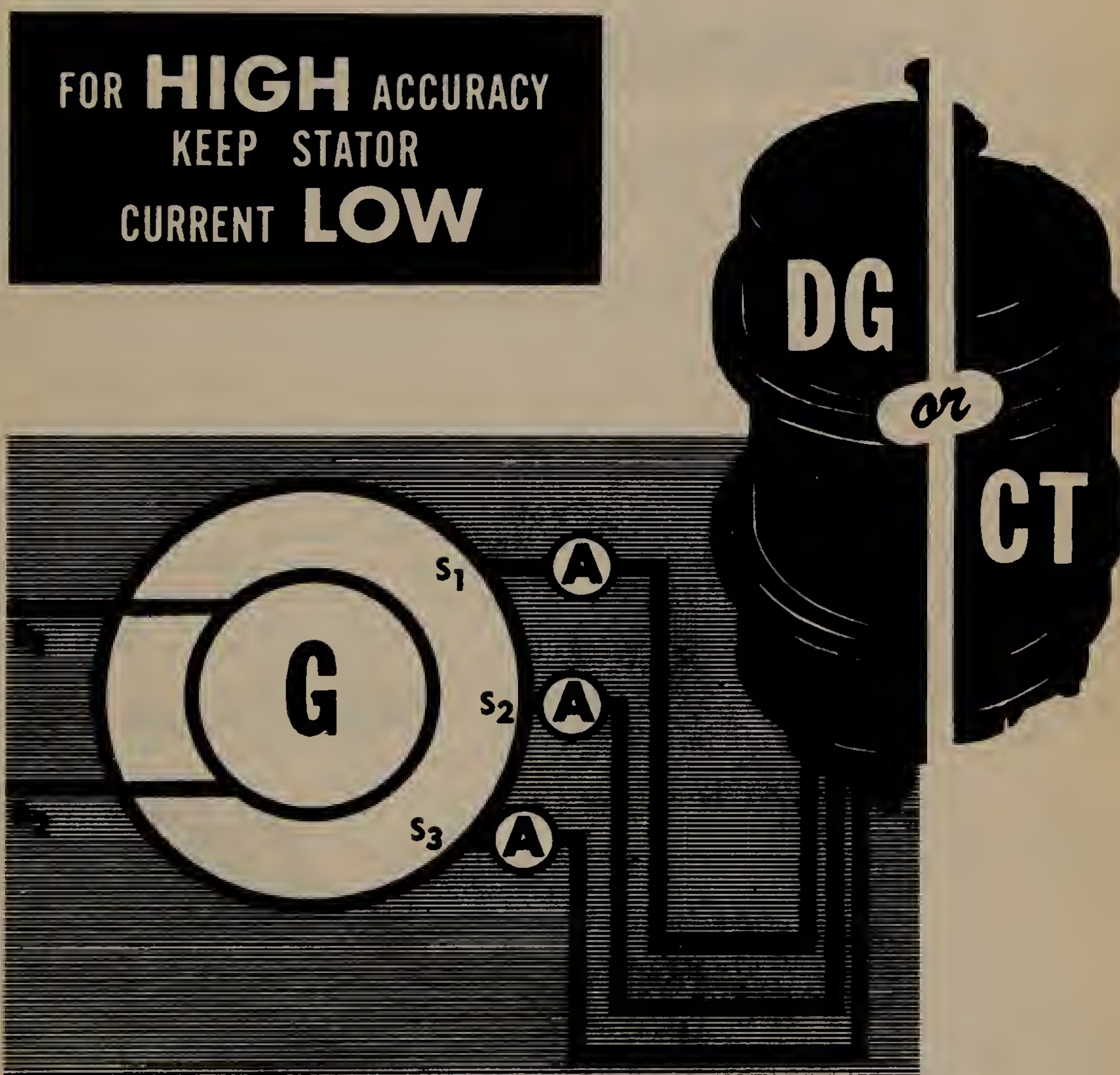


Now that you have covered the operation of all of the different types of synchros that there are, you are going to learn something about the accuracy of synchro systems and what can be done to keep this accuracy as high as possible.

Accuracy of Synchro Systems

When a synchro motor is connected to a synchro generator, very little current flows in the stators if the rotors are lined up or in correspondence. This is because the voltages induced in the motor windings almost exactly balance out the voltages induced in the generator windings. As a result, the motor is very sensitive to small changes in the position of the generator rotor, and the motor shaft will follow the generator shaft with high accuracy.

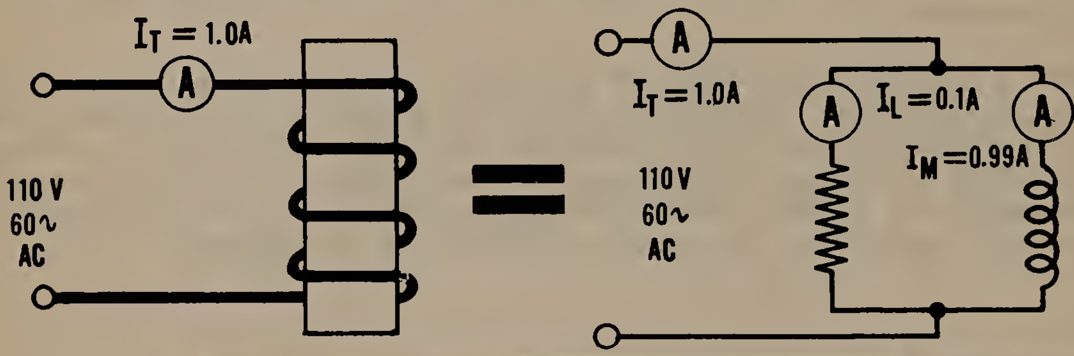
When a synchro differential or a control transformer is connected to a synchro generator, the stator currents are greater at correspondence than they are with just the motor connected. The effect of the increased stator current is to reduce the accuracy of the system. In order to keep high accuracy in a synchro system containing either synchro differentials or control transformers, the stator currents must be kept to a minimum.



In order to approach this problem with a good understanding of what to do, you are going to review some basic AC theory.

The AC Current Drawn by a Coil

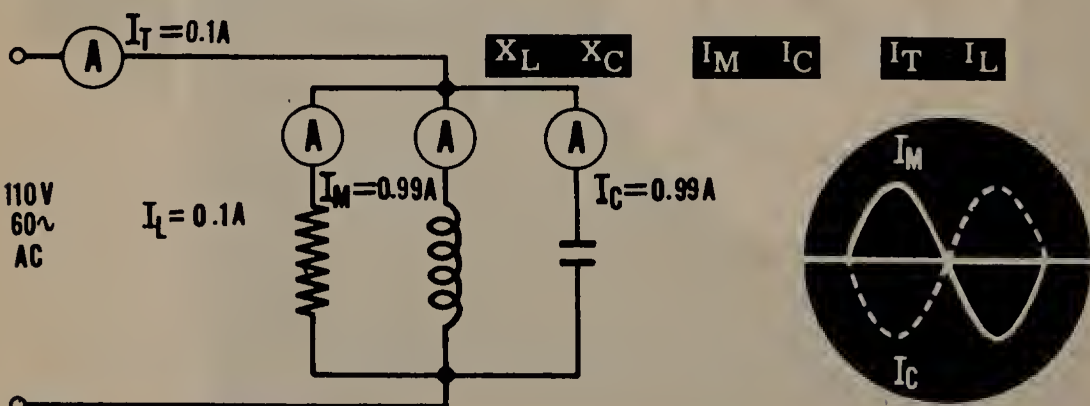
The following illustration shows a coil connected across the 110-volt 60-cycle AC line. In actual practice a coil is never a pure inductance. There is always some resistance present due to the resistance of the windings. An actual coil can therefore be represented in an equivalent diagram as a pure inductance in parallel with a very high resistance.



EQUIVALENT DIAGRAMS

I_T stands for the total line current. In a synchro system containing a DG or CT, I_T would represent the current that flows in the stator windings. I_L stands for the loss current which is that part of the total current that is in phase with the line voltage. It makes up a very small part of I_T. I_M represents the magnetizing current flowing through the coil. It is this current that we would like to eliminate because it makes up most of the line current.

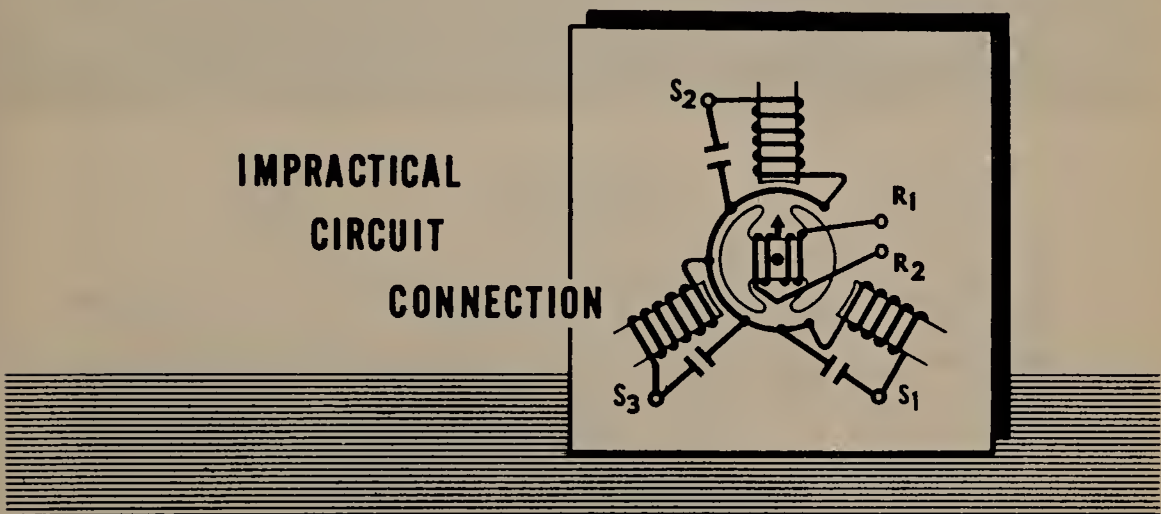
Suppose a condenser is hooked up across the coil, and suppose that its capacity is adjusted so that its reactance equals the reactance of the coil. Since the two reactances are equal, the current they draw from the line must also be equal. However, these currents are going to be 180 degrees out of phase since I_M is a lagging current with respect to the line voltage and I_C is a leading current with respect to the line voltage. Since these two currents are equal in magnitude but opposite in phase, they cancel each other out in vectorial addition. The total line current is now equal to the loss current or 0.1 amperes.



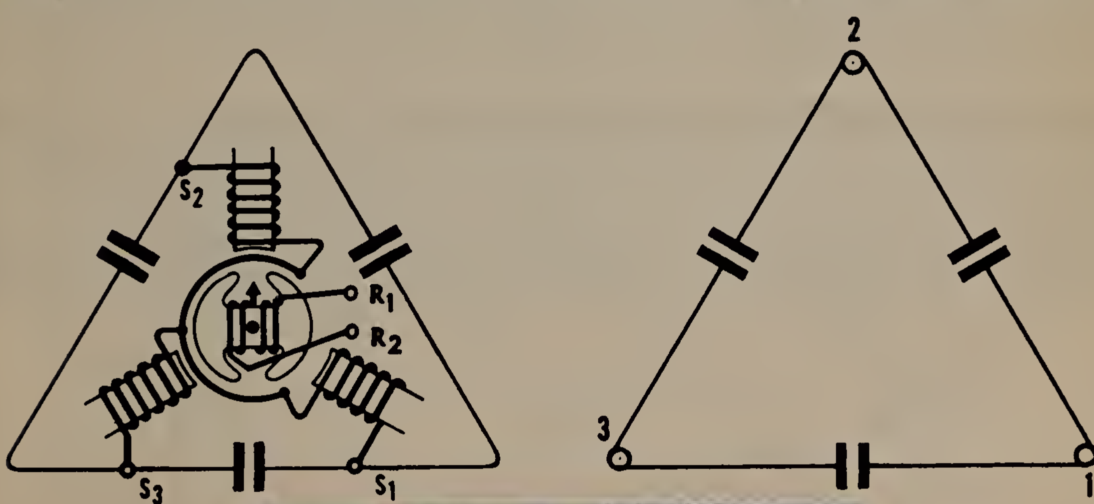
CONDENSER CURRENT CANCELS COIL CURRENT

How Synchro Capacitors Are Used

You have learned that by adding a condenser of the right value across a coil, the line current can be greatly cut down. If the coil used in the discussion on the previous sheet represents a stator winding of a CT, then, by simply placing the right size condenser across this winding, the stator current can be greatly reduced. This will help to improve the accuracy of the synchro system.



The method of connecting condensers across the individual stator windings is impractical because it requires that the common connection be brought to the outside of the synchro. This is not done with synchros and so another method has been devised to connect up the condensers which works just as well. The diagram shows a practical way of connecting up condensers across the stator windings to cancel out the magnetizing currents.



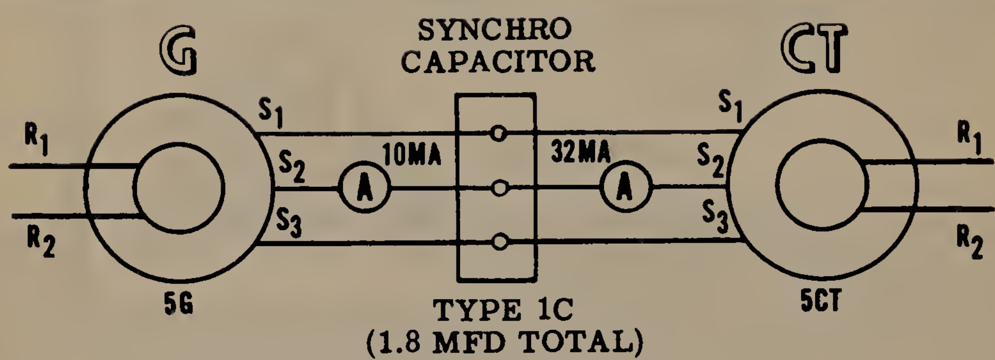
THE SYNCHRO CAPACITOR

Now the condensers can be connected to the three external leads S_1, S_2 and S_3. The three condensers usually come as a unit mounted in a case with three external connections as shown. The entire unit is called a syn chro capacitor. The synchro capacitor is made in many sizes to meet the requirements of all sizes of standard differentials and control transformers. The synchro capacitor is rated by its total capacity, which is the sum of the individual capacities in the unit.

How Synchro Capacitors Are Used (continued)

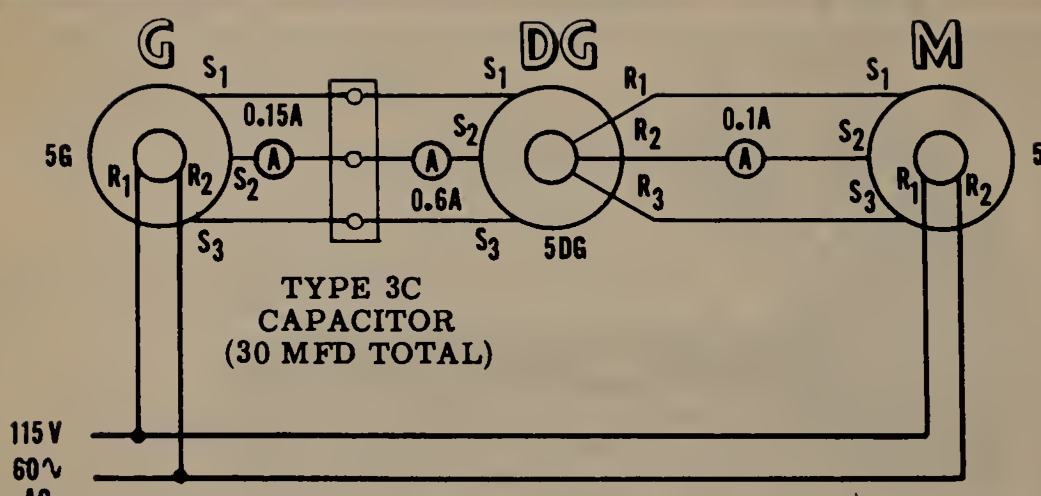
The following diagrams show how connecting a synchro capacitor into a synchro system reduces the stator current, thus increasing the efficiency of the system. The current reading between the synchro capacitor and the CT or differential synchro is the stator magnetizing current which is canceled out. This is the current that would normally flow in the stator of the generator if the synchro capacitor were not connected. The other current reading is the reduced line current after the magnetizing current has been canceled. The synchro capacitor is always placed physically close to the differential or control transformer whose current it corrects.

THE USE OF CAPACITORS WITH CONTROL TRANSFORMERS



Notice that the current is reduced from 32 ma. to 10 ma.

THE USE OF CAPACITORS WITH A SYNCHRO DIFFERENTIAL



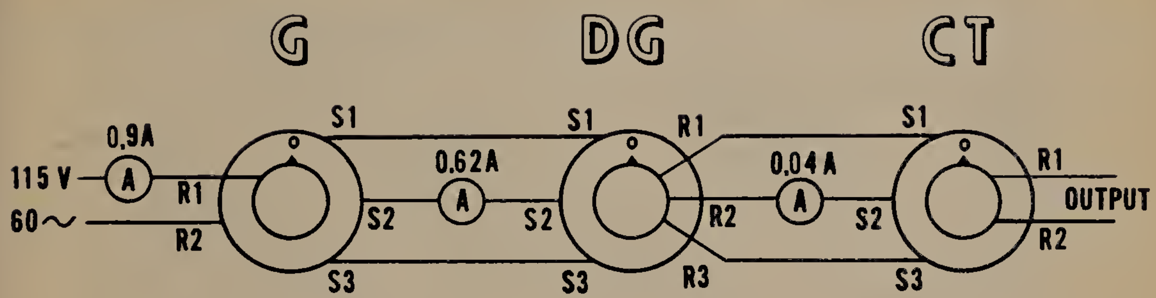
In the above example, the current is reduced from 0.6A to 0.15A. This reduction of current has the effect of reducing the motor position error by 10 percent.

How Synchro Capacitors Are Used (continued)

Some synchro systems contain both a differential generator and a control transformer. In this case there will be large stator currents flowing in the generator, since it must supply all the losses as well as the magnetizing current for both synchros.

GENERATOR MUST SUPPLY EXCITING CURRENTS

TO BOTH UNITS . . . . .

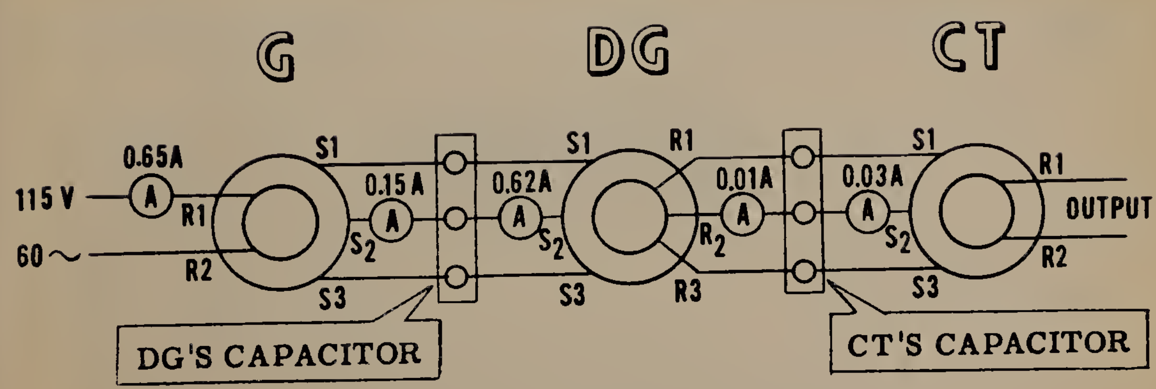


Since the normal stator current for 5 G or 5 M is about 0.6 amp., the current flowing in the stator of the generator is excessive and will cause inaccurate operation of the synchro system.

Adding synchro capacitors greatly decreases the stator currents and improves the efficiency of the system.

THE USE OF CAPACITORS WITH A DIFFERENTIAL GENERATOR

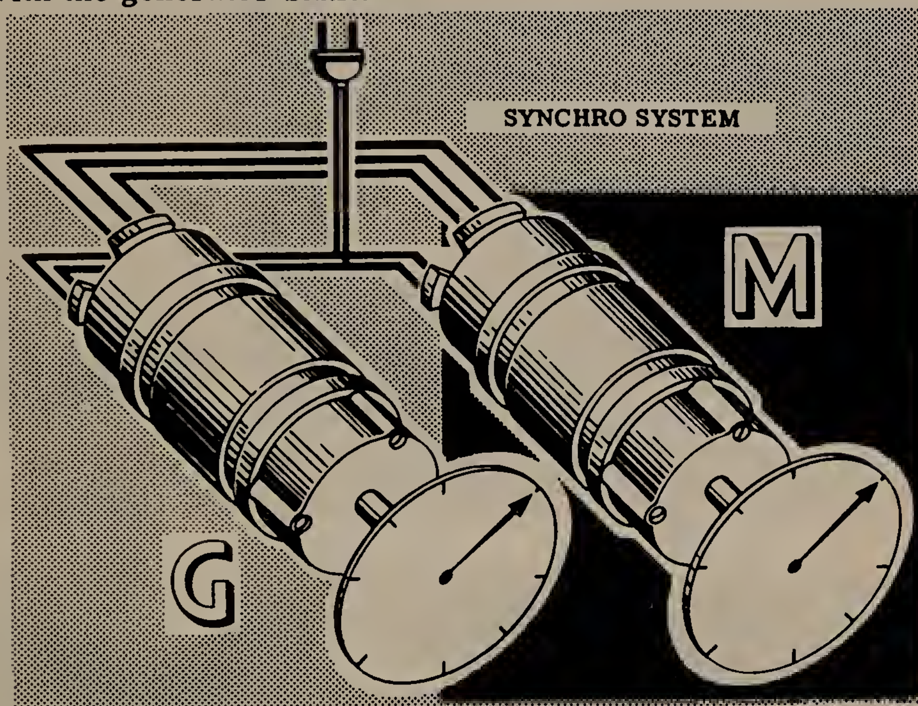
AND A CONTROL TRANSFORMER



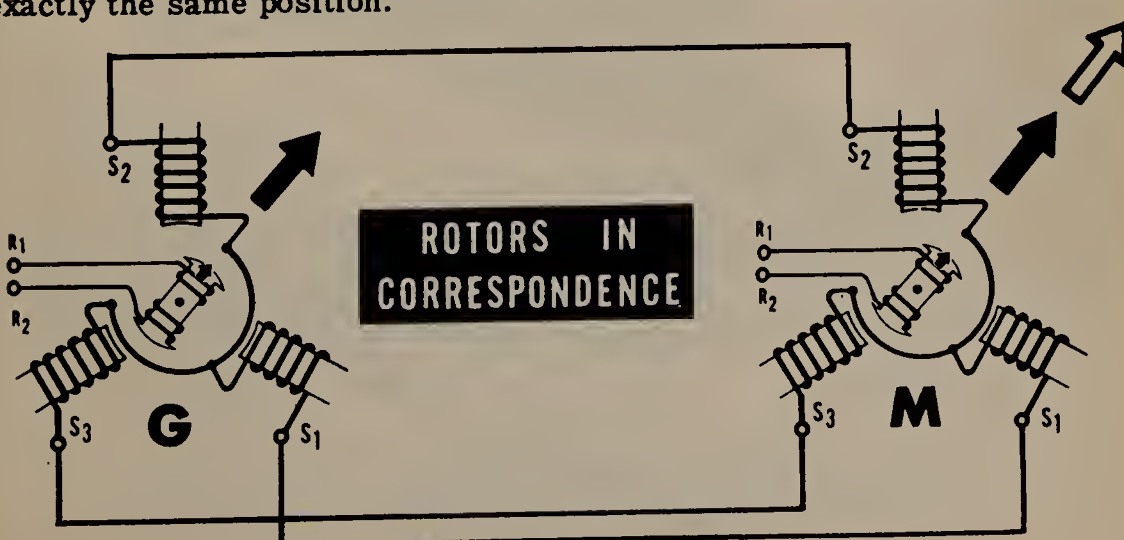
CONCLUSION TO SYNCHRO FUNDAMENTALS

With your study of synchro capacitors, you have concluded your study of synchro fundamentals. Your next step will be to study fundamentals of servo systems. Before you proceed, suppose you review what you have already learned about synchros.

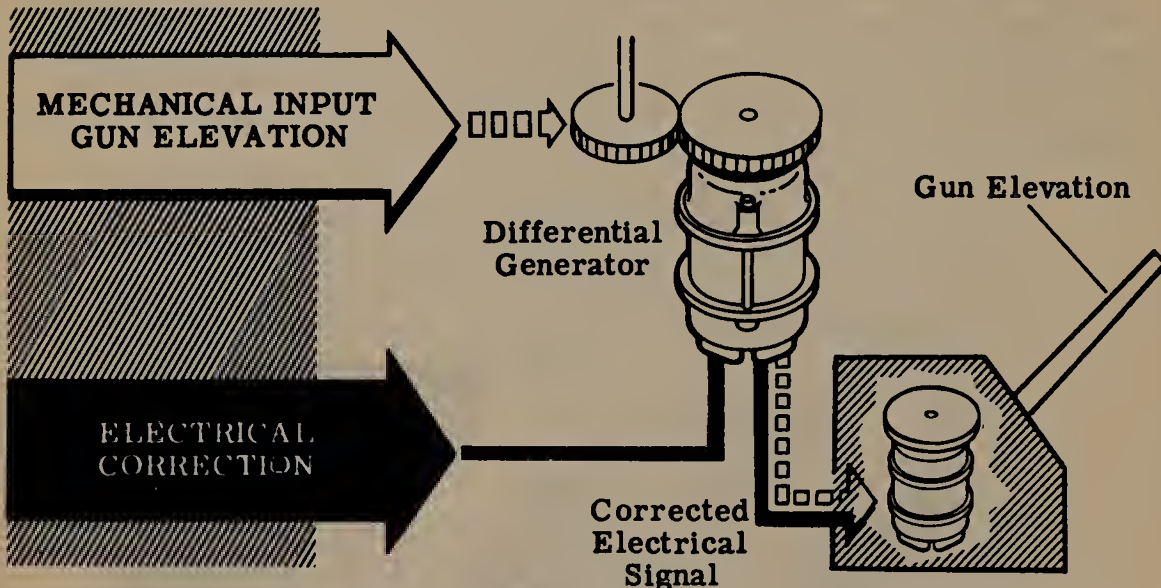
You know that synchros are used to transmit data or information between two points by means of electrical signals. The first two synchros that you studied were the generator-motor team. You learned that when the generator shaft is turned, an electrical signal is transmitted from the generator to the rotor which causes the motor shaft to turn in synchronization with the generator shaft.



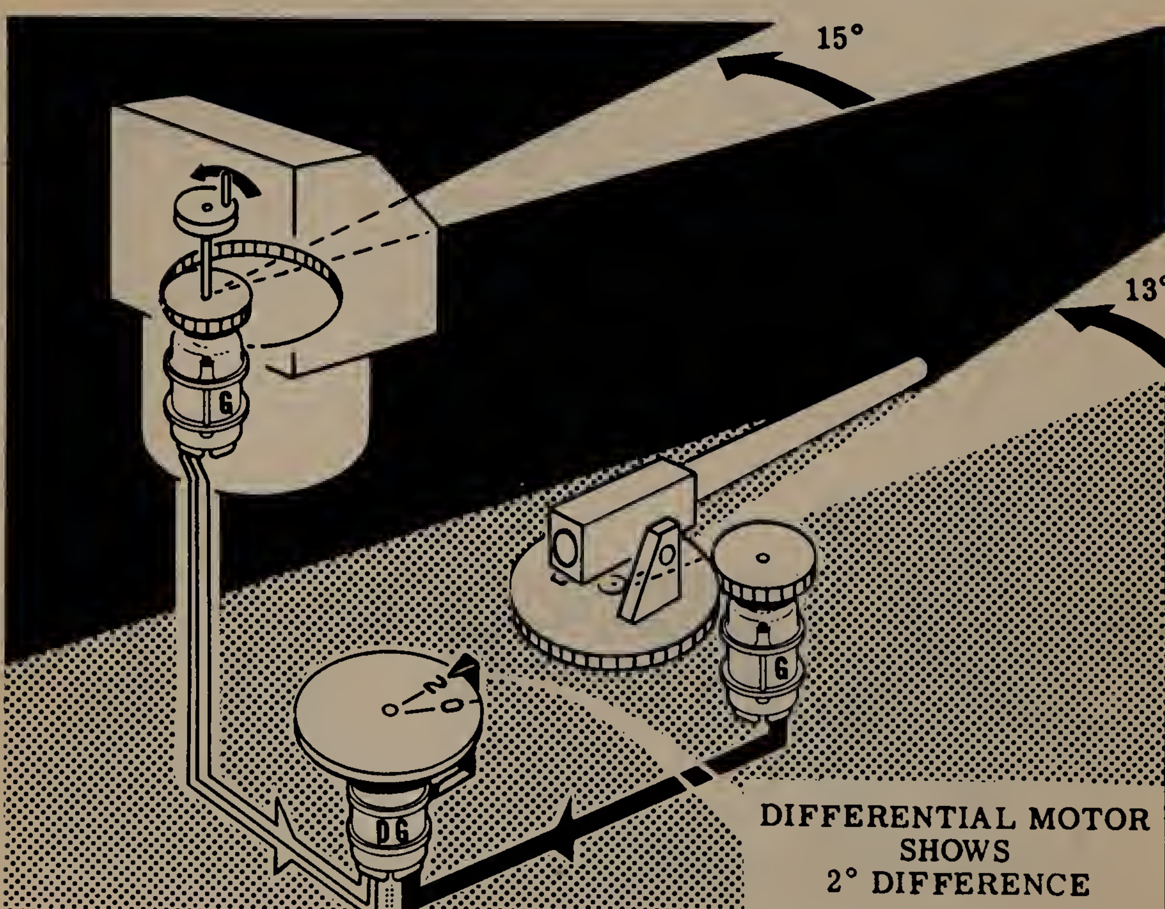
You learned that the electrical signal which is transmitted from the generator to the motor generates a magnetic field in the stator of the motor which is in correspondence with the generator rotor magnetic field at all times. The rotor of the motor, being an electromagnet, will be attracted by the stator field. This attraction causes the rotor shaft to turn until it is lined up with the stator field. When this happens,the two rotors are in exactly the same position.



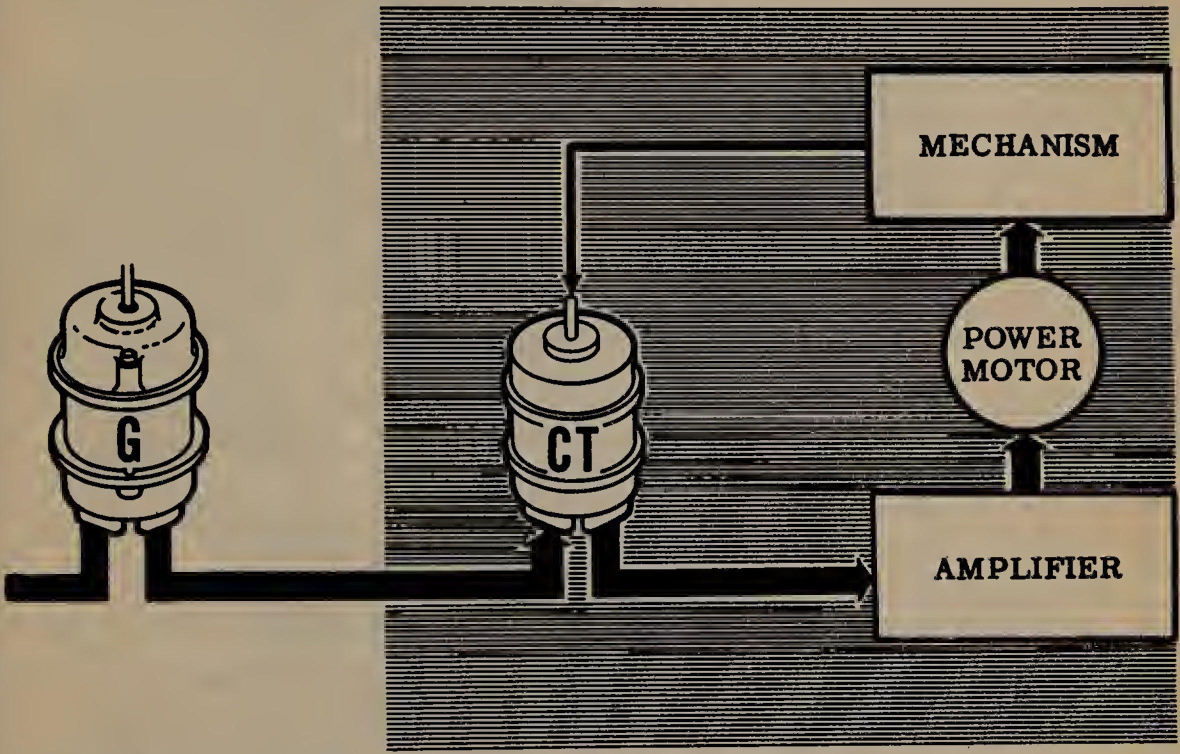
The next synchro that you learned about was the differential. You found out that the synchro differential generator could be hooked up to give an electrical signal output which is either the sum or difference between two signal inputs—one being a mechanical signal and the other being an electrical signal.



Similarly the differential motor gives a mechanical signal output by rotating its shaft an amount equal to either the sum or difference between two electrical signal inputs.

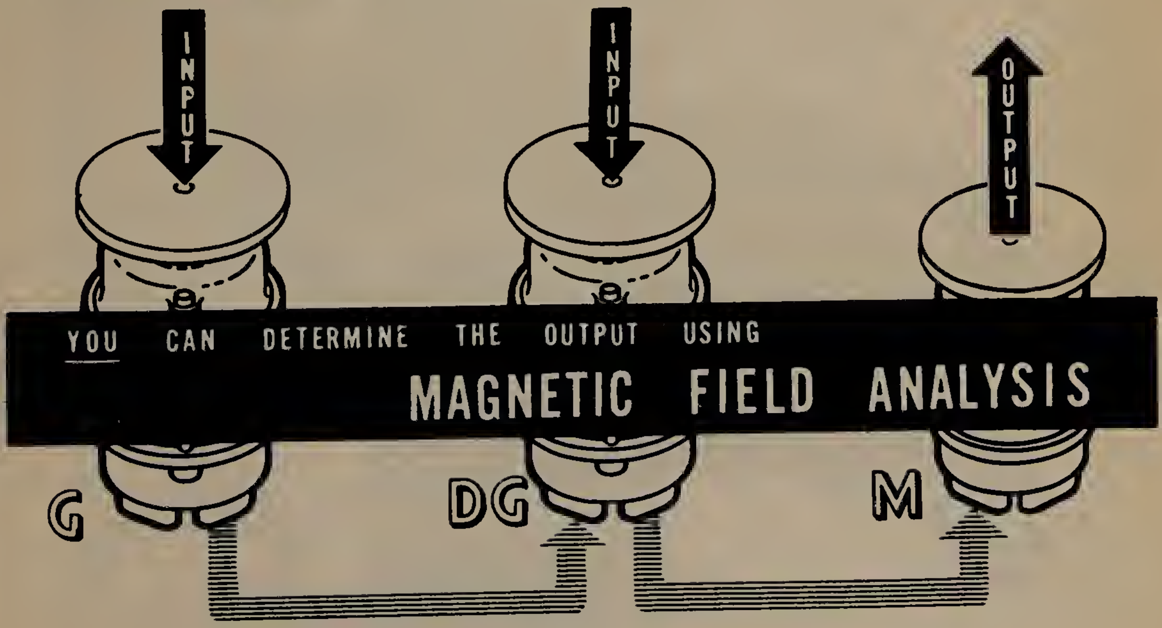


Then you studied the control transformer. You found out that the control transformer gives an electrical signal output called an error signal. The error signal can be amplified by a follow-up which provides the power to position a heavy mechanism.

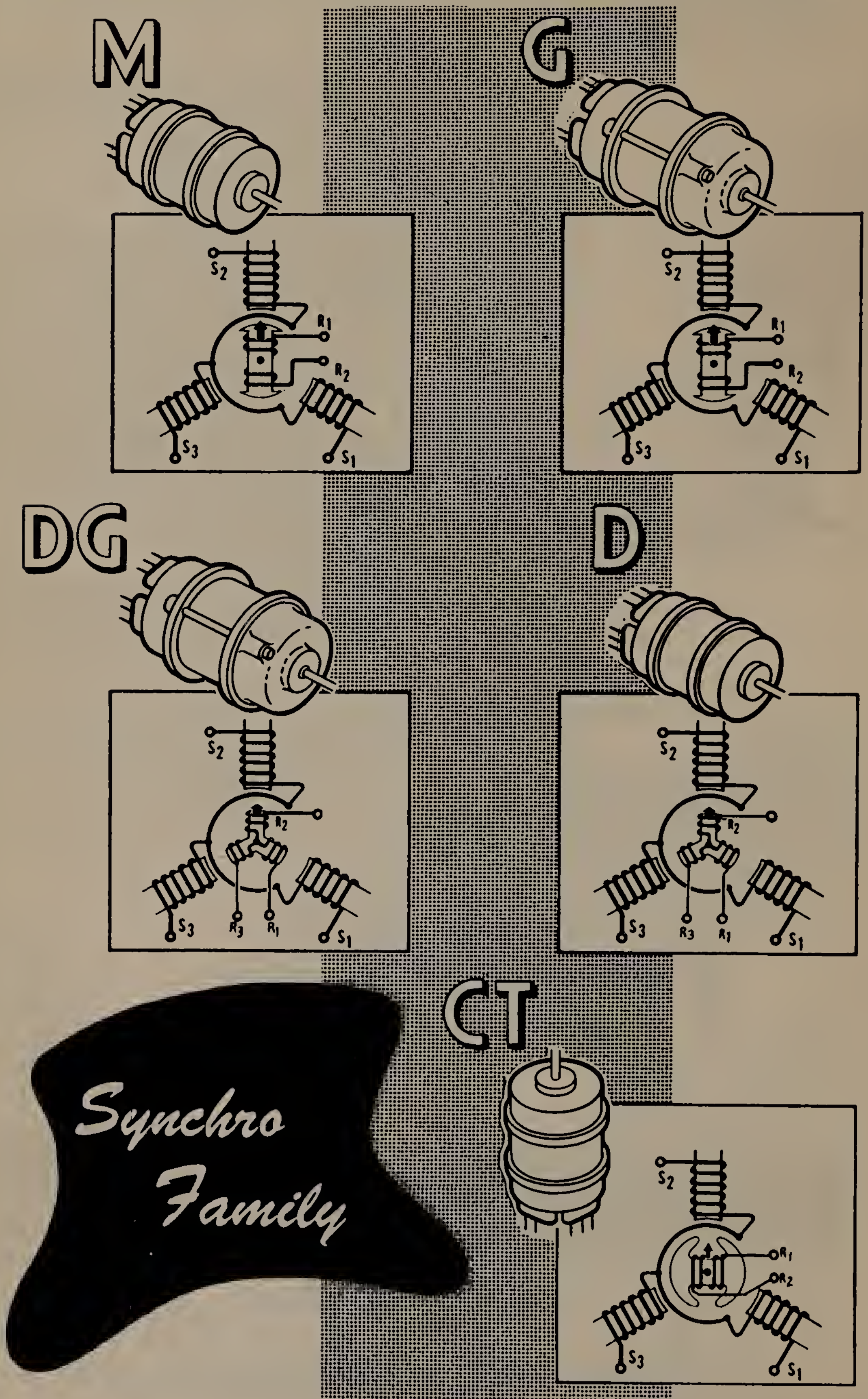


And finally you studied synchro capacitors which are used to increase the accuracy of synchro systems.

The most important thing you learned by reading this section was how to trace a signal through a synchro system, using a magnetic field analysis. In this manner you can figure out what will happen at the output of a synchro system when either a mechanical signal or an electrical signal or both types of signals are fed into the system.

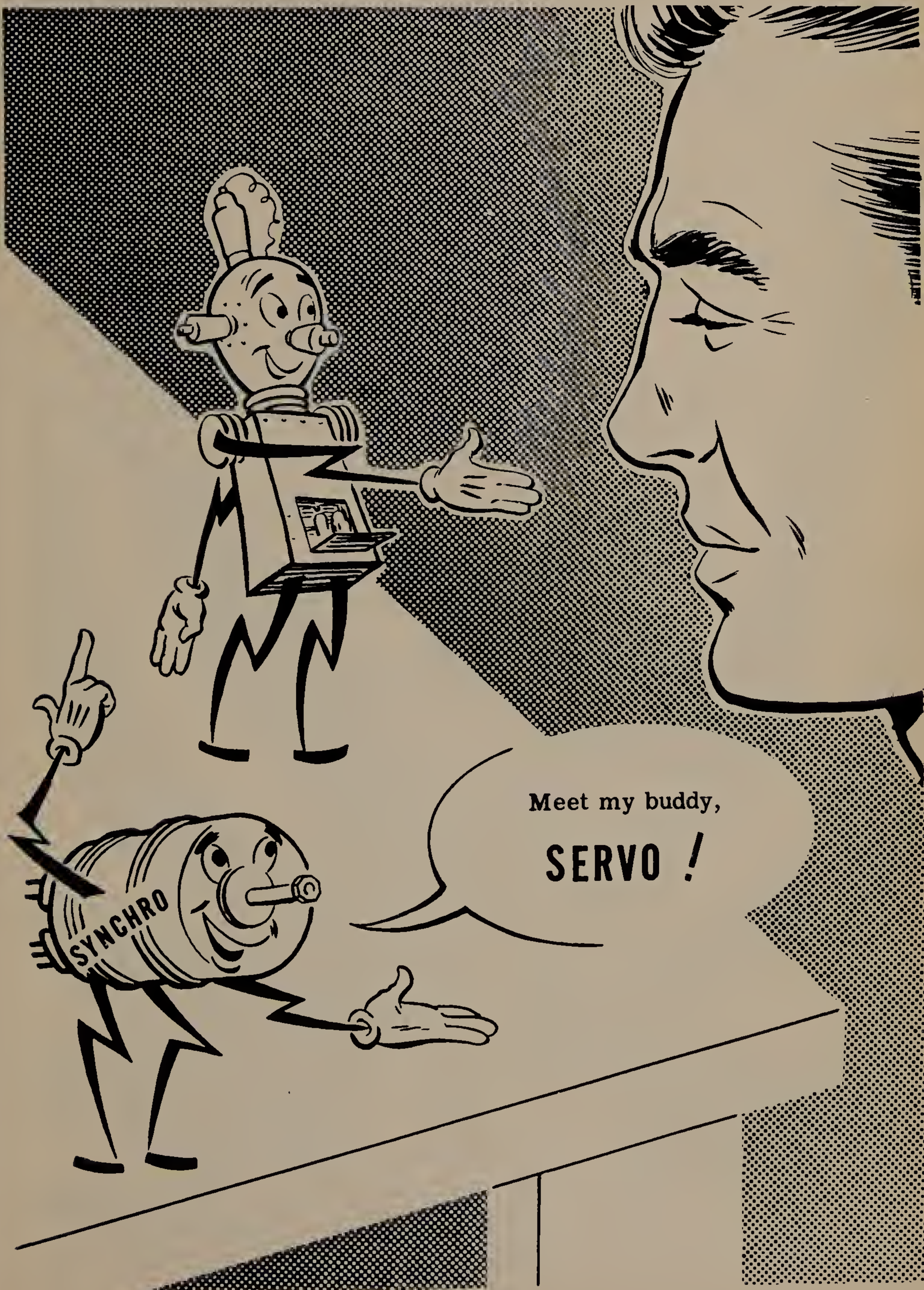


In conclusion, here are the members of the synchro family once again.



Having finished your study of synchros, you are now ready to study servo systems and see how they do the complex jobs of positioning, rate controlling and calculating.

Let's go ahead and find out all about servos and how they are used in actual equipment.



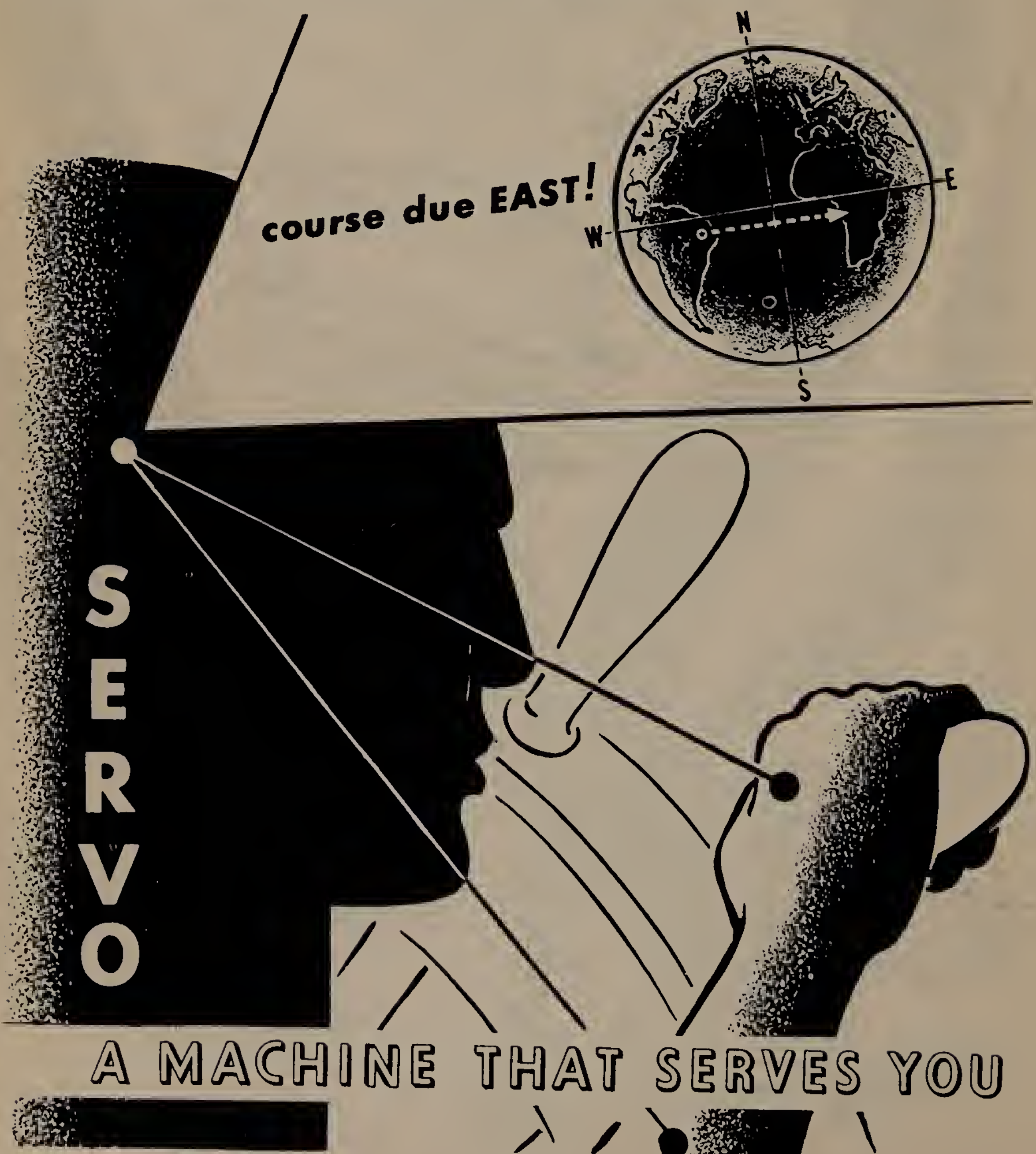
What a Servo Is

A servo is a machine or a group of machines that is actually capable of thinking. Its thinking, however, is confined only to the job it was designed to do—and then only about certain things concerning that job. When a servo is doing a job it was designed to do, it surpasses the combined efforts of the human brain, nerves and muscles. A servomechanism will do a superhuman task as long as it is supplied with power and as long as it is not damaged. It will do this job without ever making a mistake and without rest. In doing its own particular job a servomechanism can think.

What a Servo Is (continued)

If you analyze the word servomechanism, you will find it means a machine that serves. In other words, a servomechanism takes an order and carries it out, correcting any errors caused by outside forces as well as any errors made within itself. In carrying out the order, a servomechanism determines the type and the amount of difference between what should be done and what is being done. Having determined this difference, the servomechanism then goes ahead to change what is being done to what should be done.

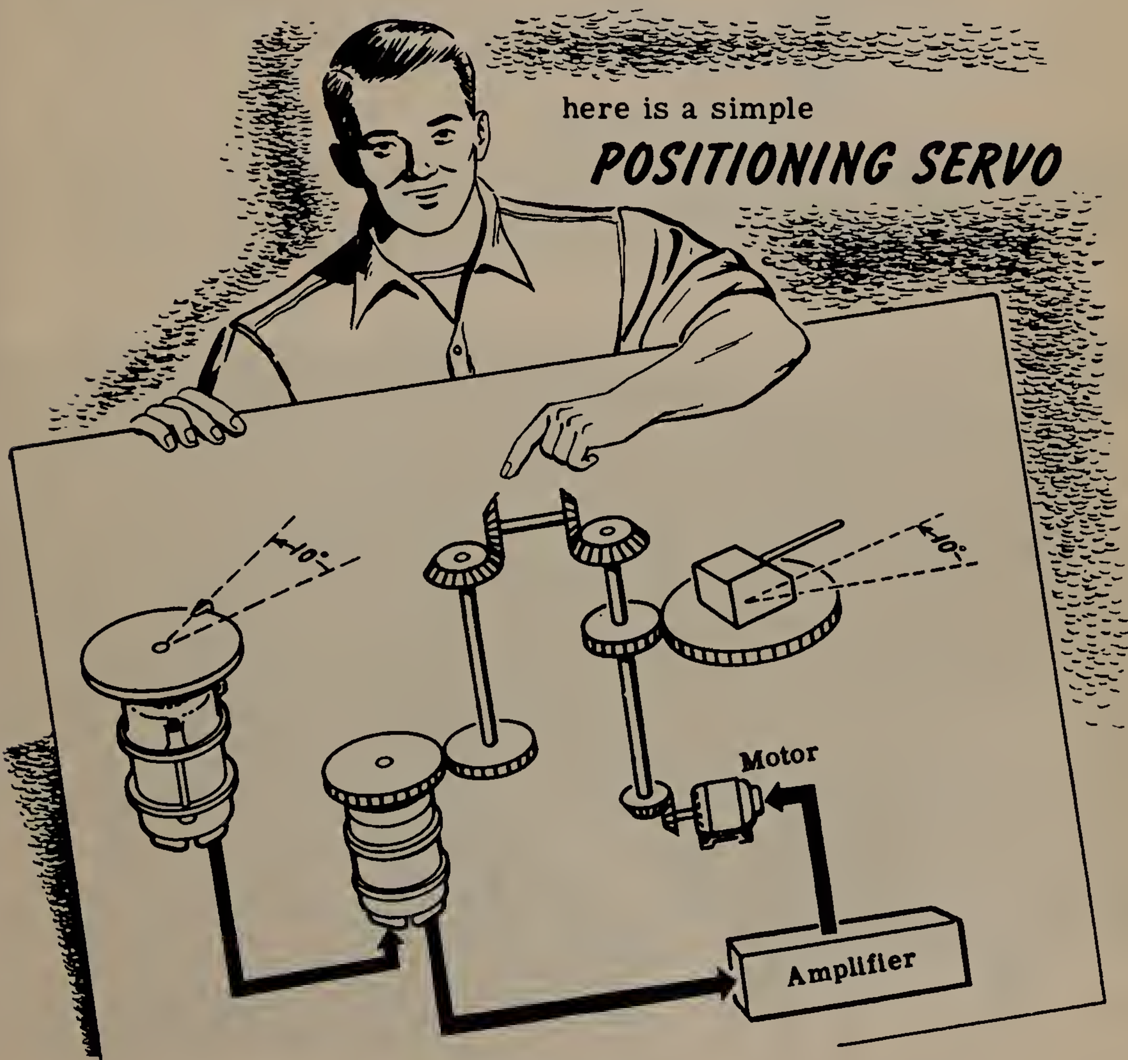
Because of these abilities a servomechanism can be designed, for example, to keep a ship on a fixed course, regardless of wind, ocean currents and waves which try to drive the ship off its desired course.



Positioning Servo

You have found out one application of a servomechanism--to automatically keep a ship steered along a designated course. Servomechanisms have many other uses. Some of these applications may not be as glamorous as steering a ship or flying a plane, but this is only because these particular jobs are more specialized and therefore never come before the eyes of the general public. In general, the jobs that servomechanisms fill may be broken down into three types—positioning, rate and calculating servos.

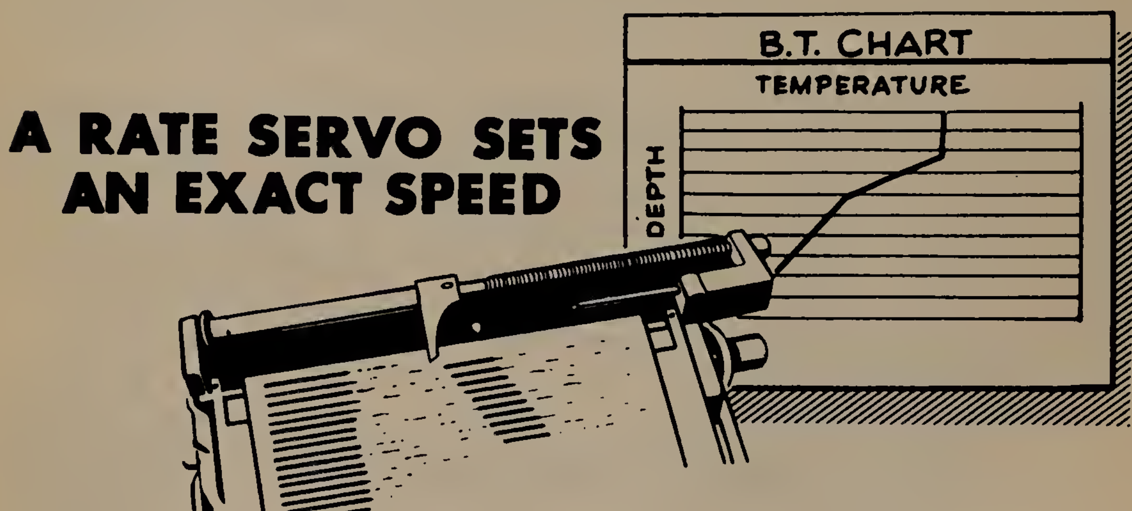
On the basis of your work with synchros, you have a pretty good idea of what a positioning servo system does. You recall that a simple synchro system cannot supply the torque required to position a heavy load. In order to do this job, the synchro team is combined with a follow-up mechanism—the entire system being called either a "servomechanism," a "servo system," or just a "servo." The block diagram below shows a simple positioning servo which has wide application in a lot of military equipment. You should remember this servo well from your readings about the control transformer.



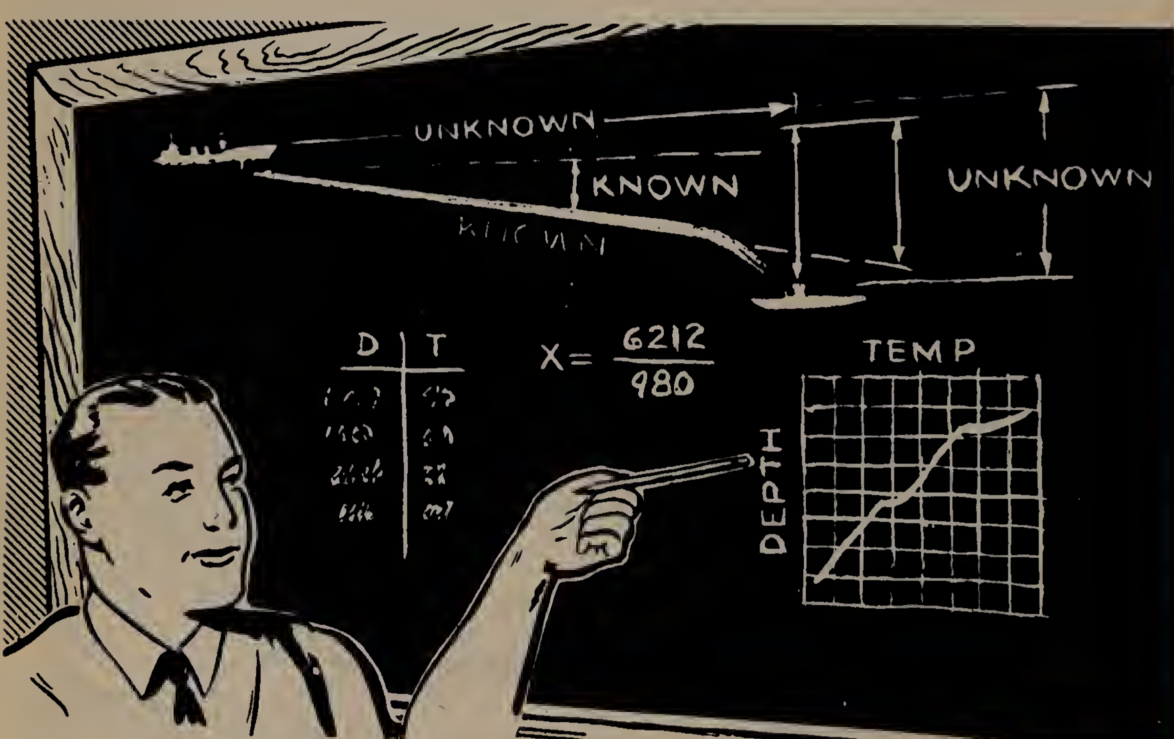
Other Types of Servos

In addition to the positioning servo there are other types of servos that find wide use. These are:

Rate Servos. This type of servo moves a load at the exact speed and in the exact direction selected by an operator or by another servomechanism.



Calculating Servos. This servo makes a desired mathematical computation from information put into it. The answer is delivered in the form of a mechanical motion, an electrical signal or a combination of these.



A Calculating Servo can compute the UNKNOWNS

The Basic Characteristics of all Servos

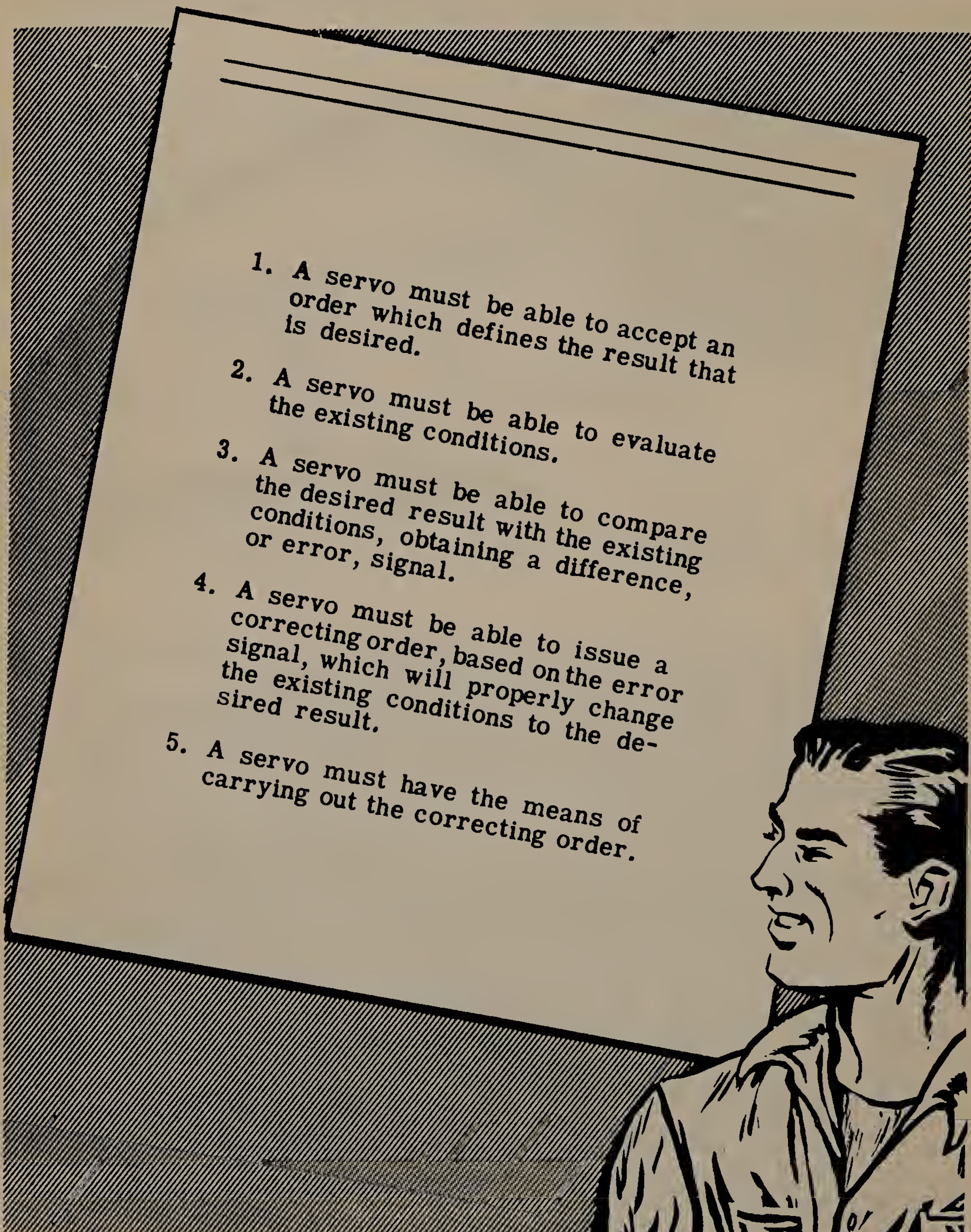
The previously mentioned servos, when found in certain equipment, may use synchro systems. However, these same basic type servos can be found minus synchro systems in other types of equipment. For example, certain fire control servos are purely mechanical. The auto pilot in a plane is also mechanical. In other words, a servo system does not necessarily have to have synchros to be considered a servo. However, all servos have certain basic characteristics which give them the right to be called servos.

We now will talk about those basic characteristics that distinguish a servo system from other machines.

Basic Requirements of Servos

Although you know servos are capable of doing jobs that require thinking, you still do not know what servos actually are and how they work.

To start with, a servomechanism is a machine whose job is to carry out an order. To do this the servo system, regardless of what type it is, must possess certain basic requirements.



DESIGNING YOUR OWN SERVO

A Servo That Will Steer a Ship

A good way for you to understand the workings of a servo system, as it goes through the previously mentioned five steps in carrying out an order, is for you actually to go through the steps in designing a servo system to do a reasonably simple job. Once you know how a simple servo works, you will be able to figure out how complex servos work.

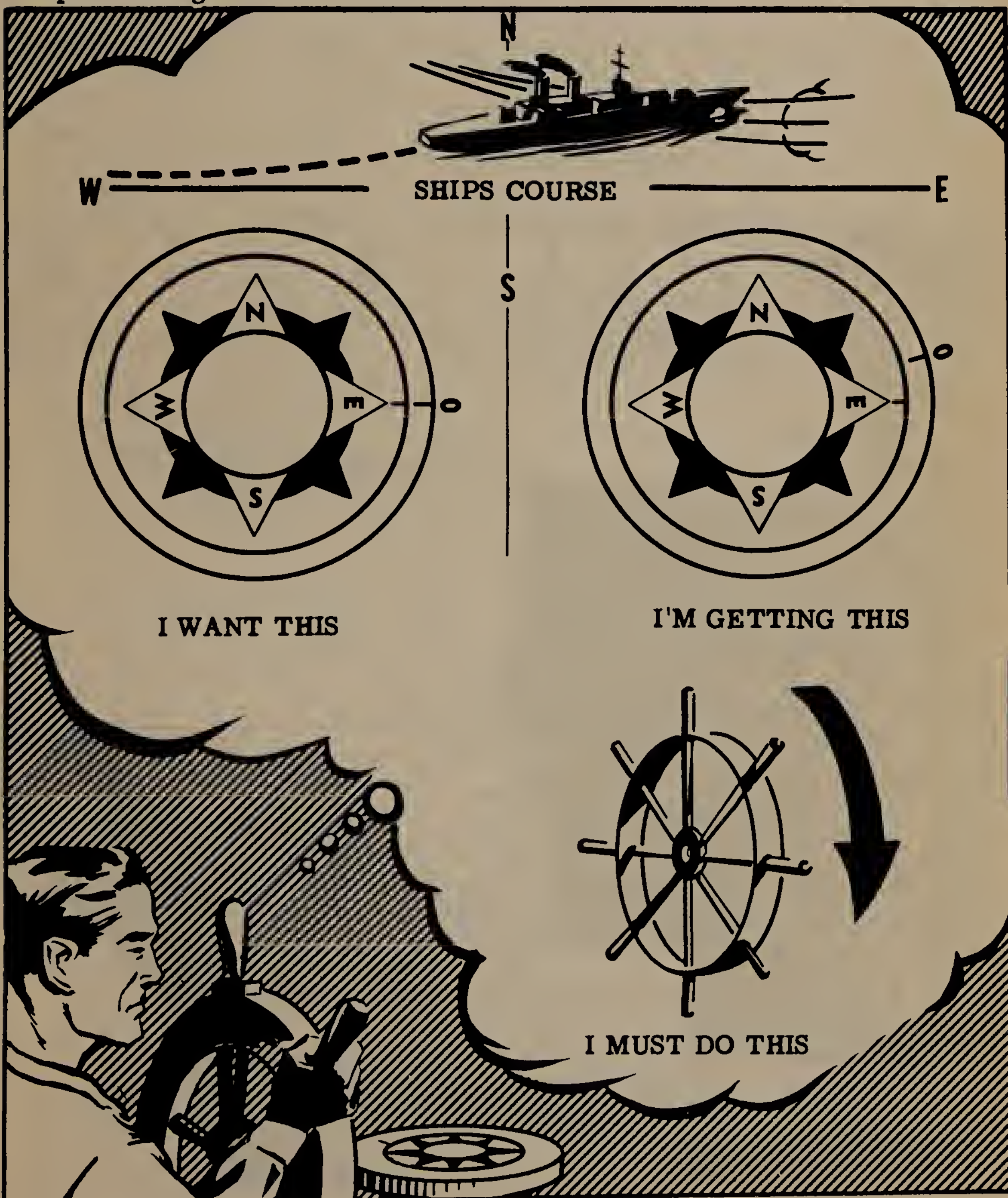
For a sample problem, suppose you decide that you want to design a servo to steer a ship along a set compass bearing.

In order to figure out the steering problems involved, you should first study the actions of a helmsman as he steers the ship along the set course.

A Servo With a Human Component

The simplest way to keep a ship headed on a desired course—say due East—is to put a <u>man</u> at the ship's wheel, with a compass to use as a standard.

A ship will not continue to go due East once it is headed in that direction. Wind, waves, ocean currents and other natural forces will make the ship veer either toward North or South. When this happens, the compass shows that the ship is no longer headed East. The helmsman's eye sees the reading of the compass, his brain concludes that the ship is heading a few degrees North of East, and his brain decides that the ship's wheel will have to be turned a certain amount and in a certain direction to turn the ship's bearing back to due East.



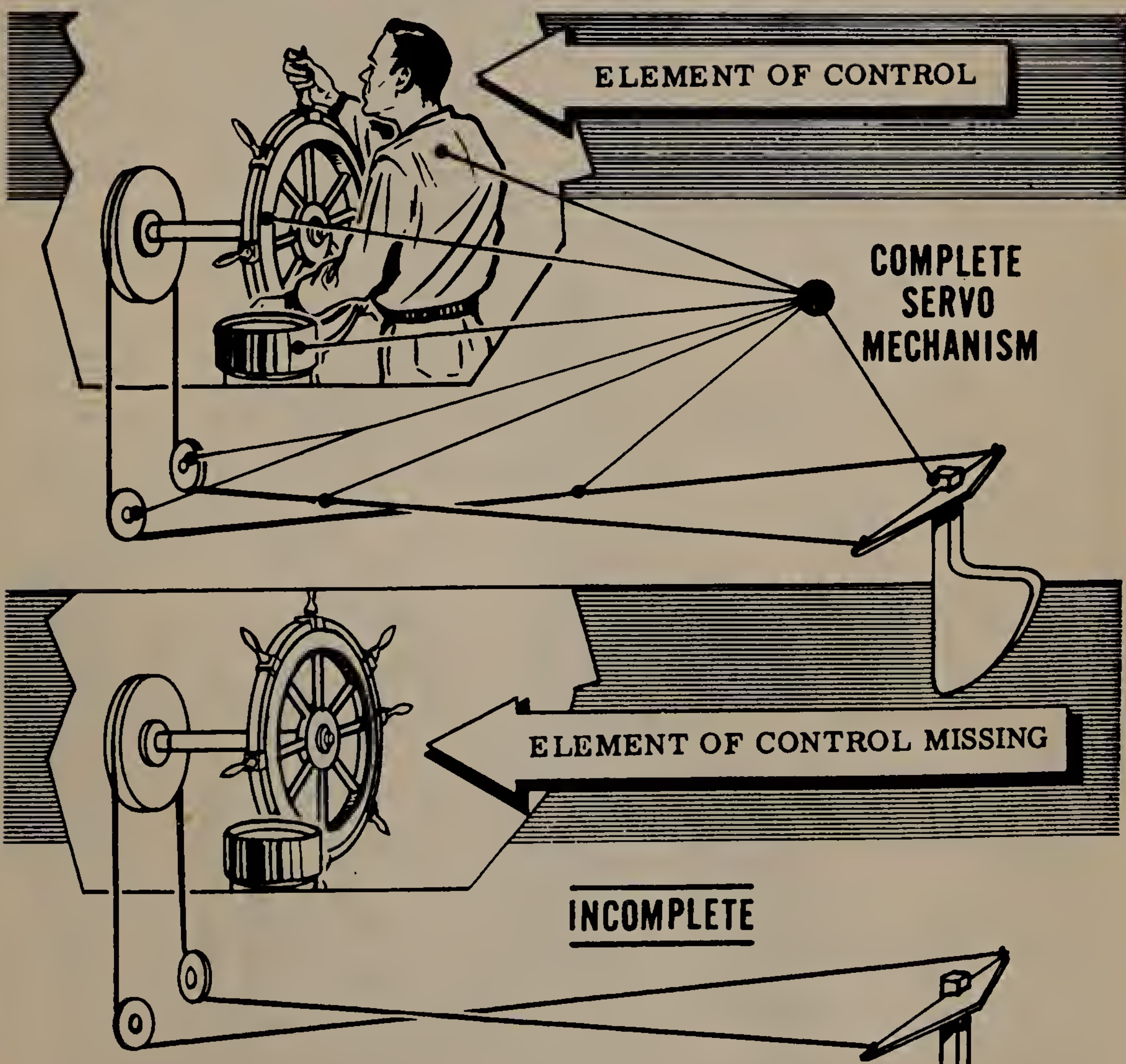
A Servo with a Human Component (continued)

The helmsman's brain issues an order to the muscles of his arms and hands to turn the wheel the desired amount. While the wheel is turning, the helmsman's eyes keep watching the compass to see the effect of the action of turning the ship's wheel. As the compass changes its readings—showing that the ship is heading back toward due East—the helmsman's brain estimates just how much the wheel must be turned back to prevent the ship's head from swinging beyond due East. The helmsman's brain issues a correcting order and his muscles turn the wheel slowly back to its original position so that, as soon as the ship is headed due East, the rudder will be in the proper position to keep it headed in that direction.

The Helmsman As the Element of Control

The helmsman, the compass, the ship's wheel, the mechanism tying the ship's wheel to the ship's rudder and the rudder itself—all make up one servomechanism. It is a servomechanism which contains a human component—but, nevertheless, it meets all the requirements of a servomechanism. The job of this particular servomechanism is to keep the ship headed due East. If any outside forces such as wind, waves or ocean currents change the ship's course from the desired setting, the servomechanism determines just what should be done to correct the error and then does it. It may not do it at once, but the overall result is that the ship heads due East.

In the above servomechanism the element of control is contained in the human component—the helmsman. The moment he is not there, you no longer have a servomechanism. Without the helmsman the system cannot accept a definite order to head due East, it cannot compare the ship's actual course with the desired course and it cannot issue an order to correct the error between actual and desired course. The system still has a compass and a ship's wheel but, without the element of control, it is useless.



Replacing the Helmsman With a Motor

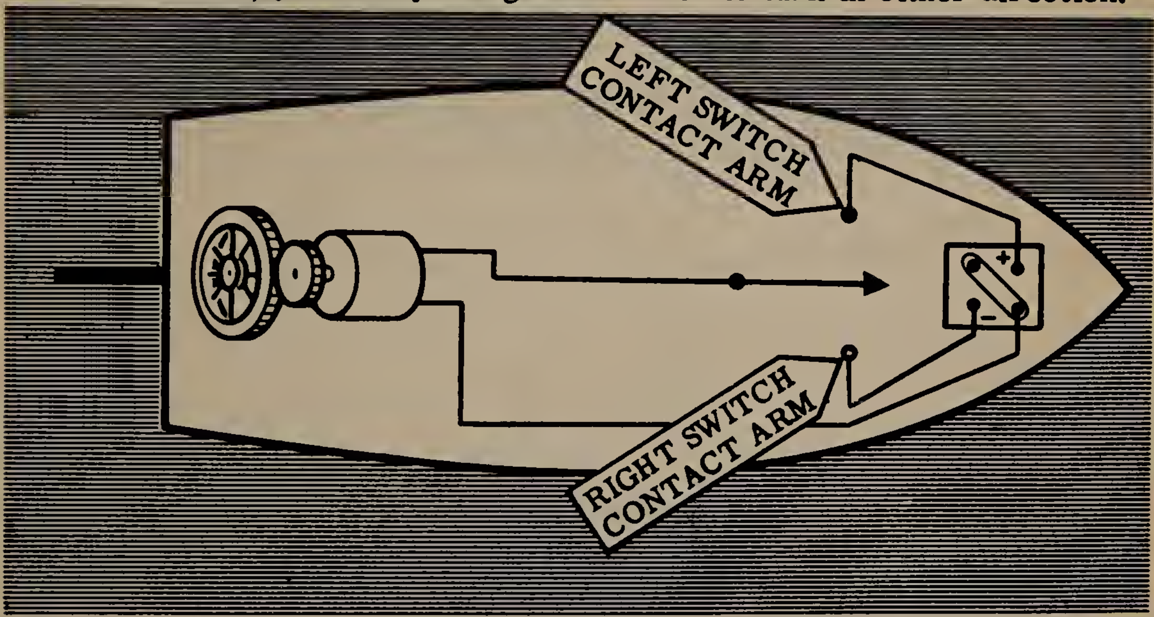
The problem you are interested in is the problem of replacing the helmsman by an electro-mechanical system. You will learn a great deal about servomechanisms by going through the steps of designing a system which will steer a ship due East without any human assistance.

It may seem to you that it is impossible to make a device that will do everything that the helmsman does. The factor of human judgment may seem difficult to replace, but you will see that it is no great problem to make a servomechanism that will steer a ship along any desired course.

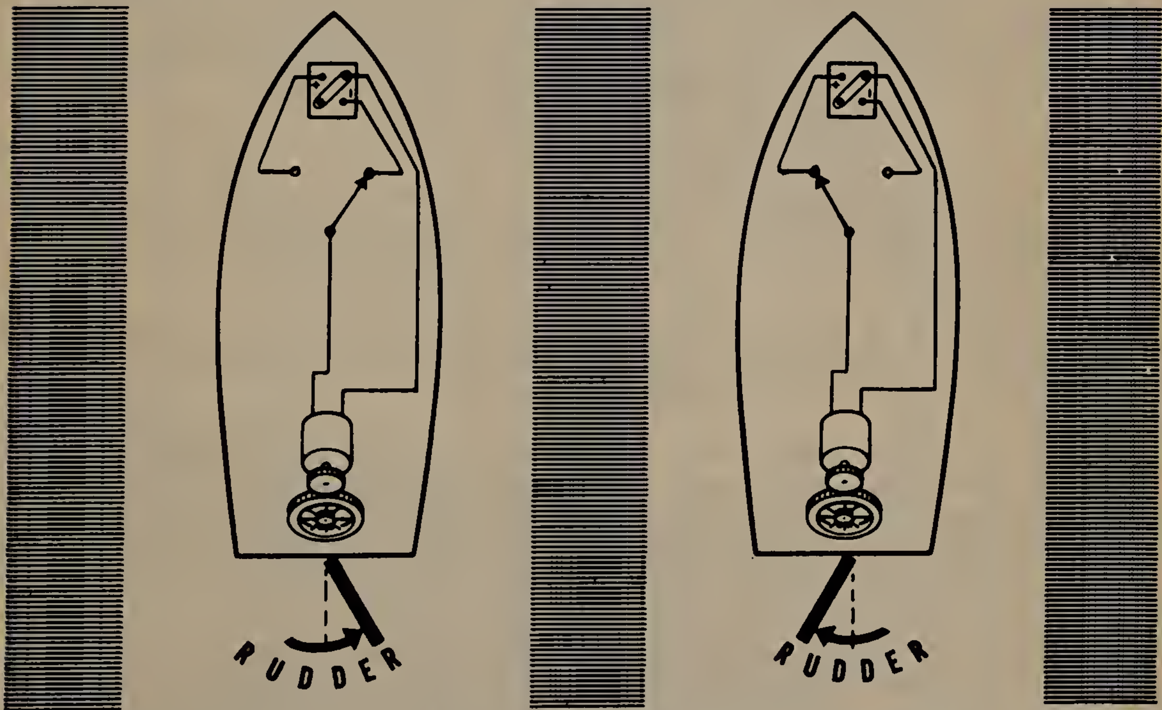
The easiest part of the helmsman to replace is his arms, which can turn the ship's wheel in either direction. A perfectly simple way of doing this is to use a motor which can turn in either direction—an ordinary DC motor will serve the purpose. It is also an easy matter to gear the motor shaft to the ship's wheel.

Connecting Up a Motor Reversing Switch

You know from your study of DC motors that this type of motor can be made to reverse its direction by reversing the connections to the power source. If you use a single-pole, double-throw switch to the power source as shown below, you easily can get the motor to turn in either direction.

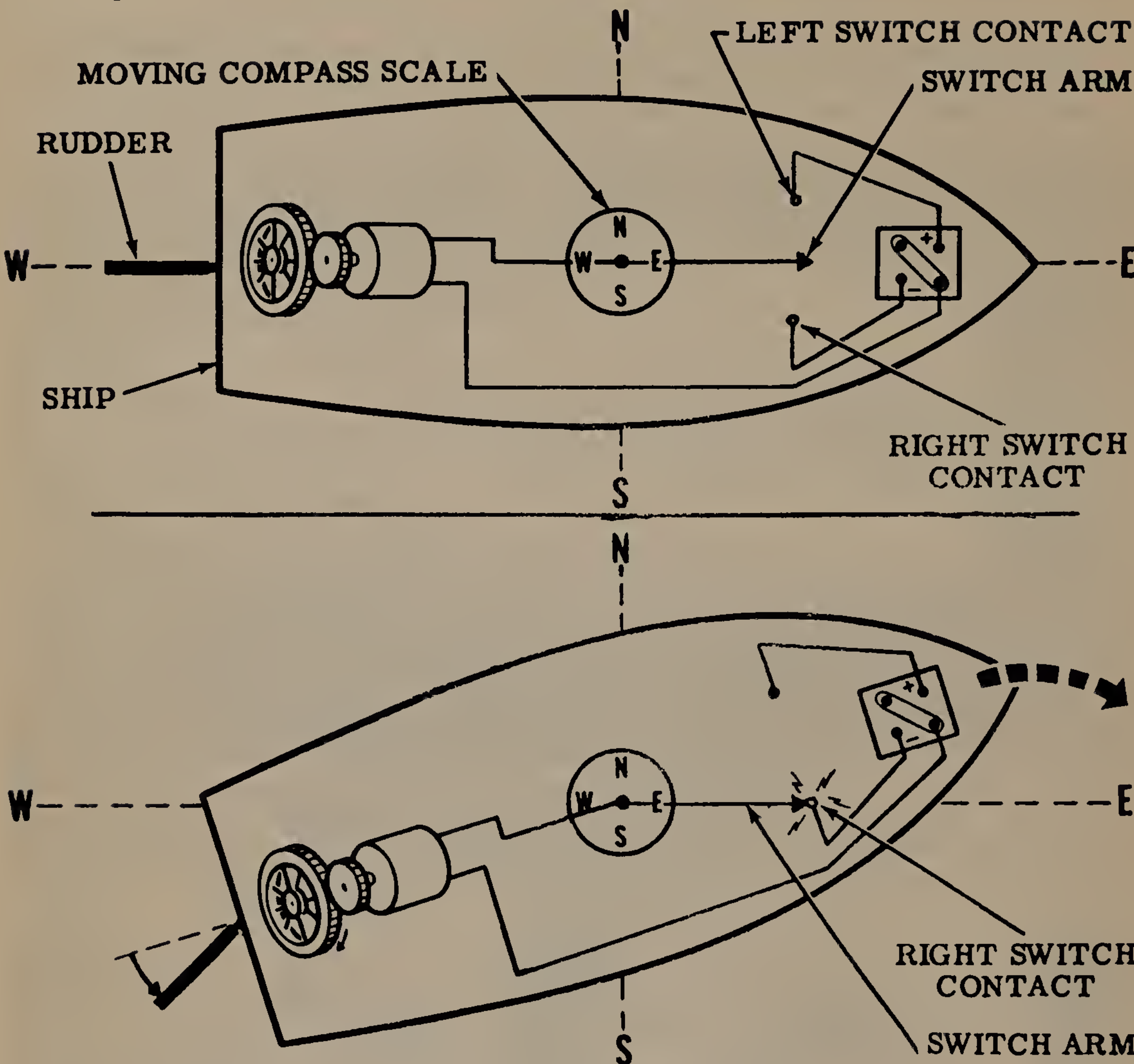


You can connect the motor so that, when the switch contact is moved to the right, the motor spins the steering wheel to the right and the rudder turns to the right. When the switch contact is moved to the left, the motor spins the steering wheel to the left and the rudder turns to the left.



The control system as it exists so far can control the bearing of the ship, but the bearing of the ship has no effect on the control system. The controlling device is not interconnected with the results of the action that is being controlled.

Hooking Up the Reversing Switch to the Compass



Your next problem is to modify the control system by making an arrangement whereby the actual direction of the ship will activate the motor to correct any error between the actual course and the desired course.

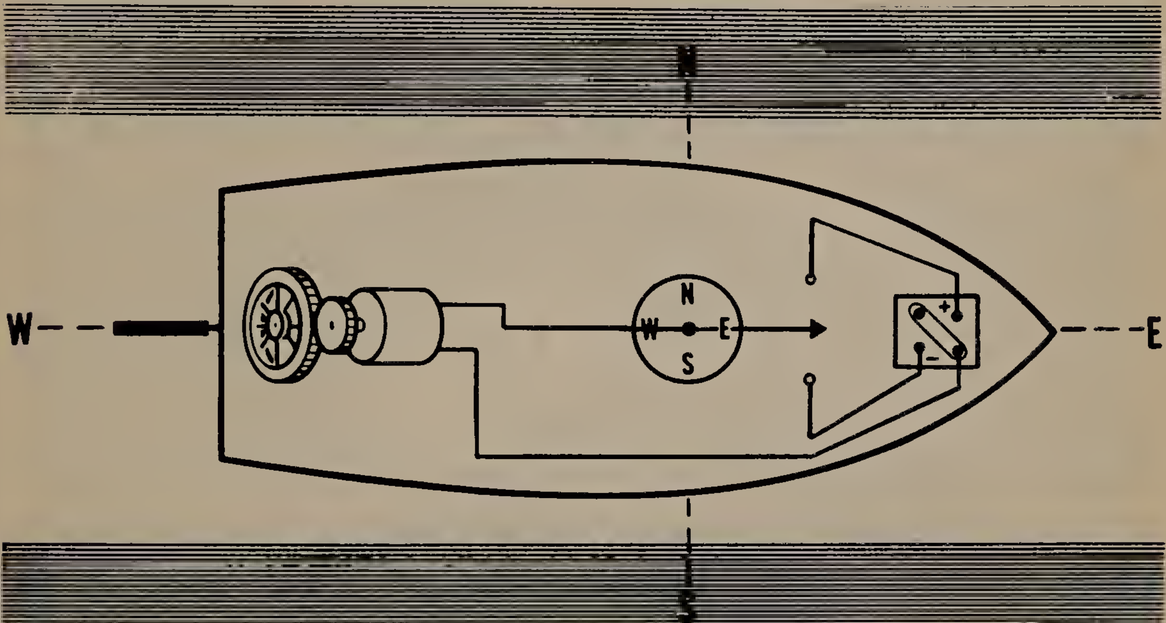
A simple way to do this is to activate the reversing switch by means of a compass. All you have to do is to connect the movable arm of the switch to the center scale of the compass as shown.

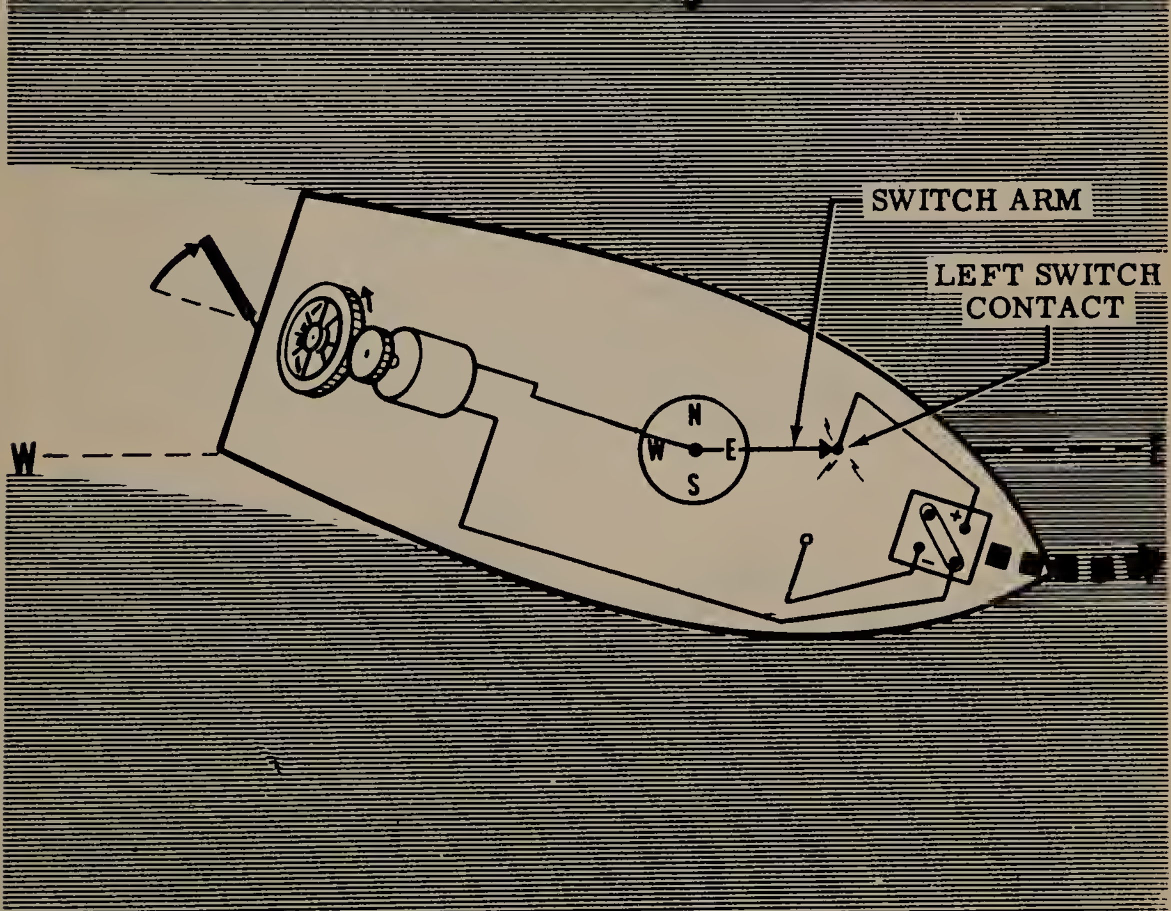
Remember that the North mark on the center scale of the compass always points North and the East mark always points East. When the ship turns away from East, the outside compass scale turns with the ship but the center scale East mark remains pointed East. Now consider what will happen if the ship turns off course.

If the ship turns to the North, the East mark of the compass will remain pointed to the East. The result of this is that the movable switch arm (fixed to the East mark) will remain pointed East and will make contact with the right-hand stationary switch contact. This will cause the motor to turn in a direction that will spin the ship's wheel so as to turn the ship back toward the East.

Your Servo in Action

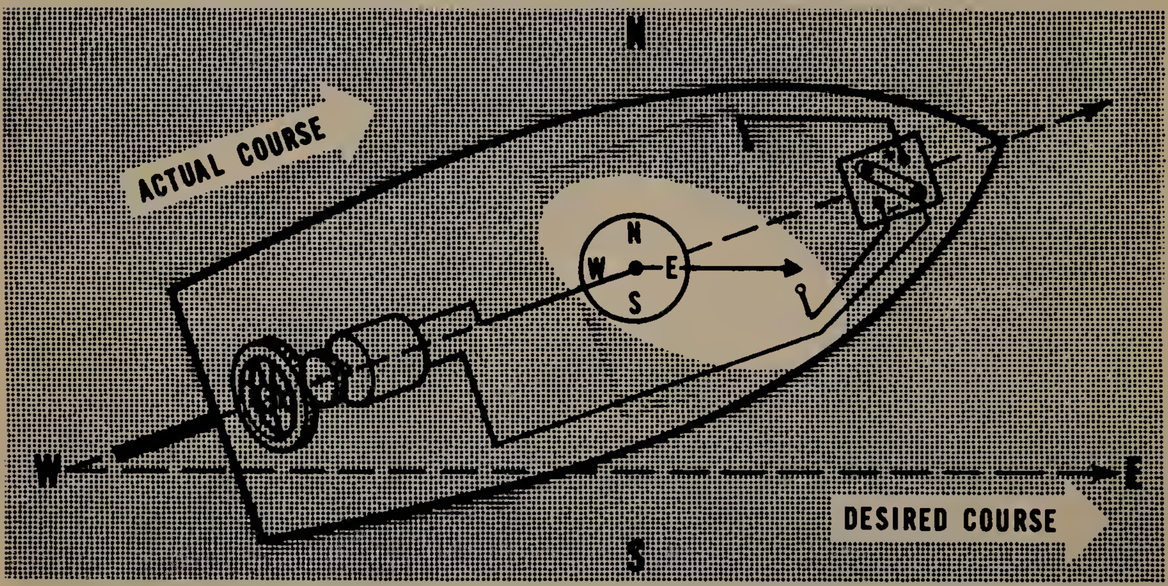
In the same manner, if the ship turns to the South, the East mark of the compass will remain pointed to the East and so will the movable arm of the motor switch. As a result, the movable switch arm will contact the left-hand stationary switch contact. This will cause the motor to turn in the direction which will spin the ship's wheel so as to turn the ship back toward the East.



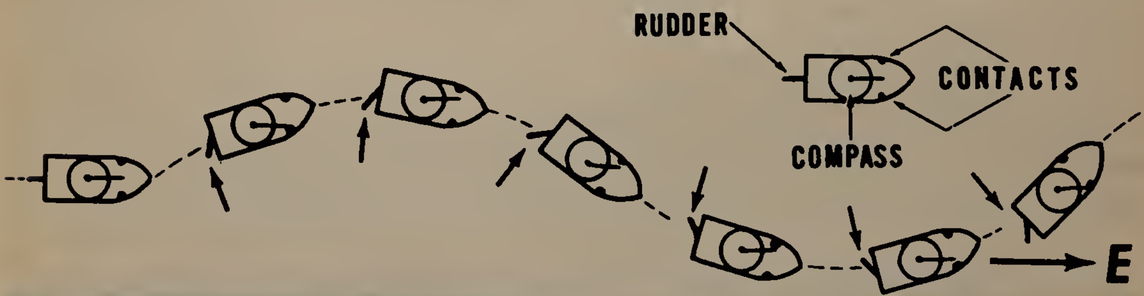


Limitations of Your Servo

One important type of trouble with this system is that it is not sensitive to small changes in the ship's direction. The motor begins to turn only when the ship is far enough off its course to close the switch on either side. It doesn't require much thought for you to see that the ship can head off course by a number of degrees just slightly less than the number of degrees required to throw the switch. Also, no matter how carefully the switch was made, there would still be a small amount of switch play required in order to open and close the motor circuit.



A very bad feature of the above effect is that there is a time delay between the turning of the ship and the spinning of the steering motor. The ship must go off its course enough to close the switch on one side. At this moment, the motor spins away and turns the rudder to counteract this error in course. As soon as the rudder begins to turn, the ship begins to correct its course. The switch contact opens and the motor stops. The rudder, however, remains turned in the same direction until the ship is turned enough past the desired bearing to throw the switch in the opposite direction. The overall effect is that, in correcting an error, that error is overcorrected and causes another error in the opposite direction. This will cause the ship to oscillate back and forth about the desired course.

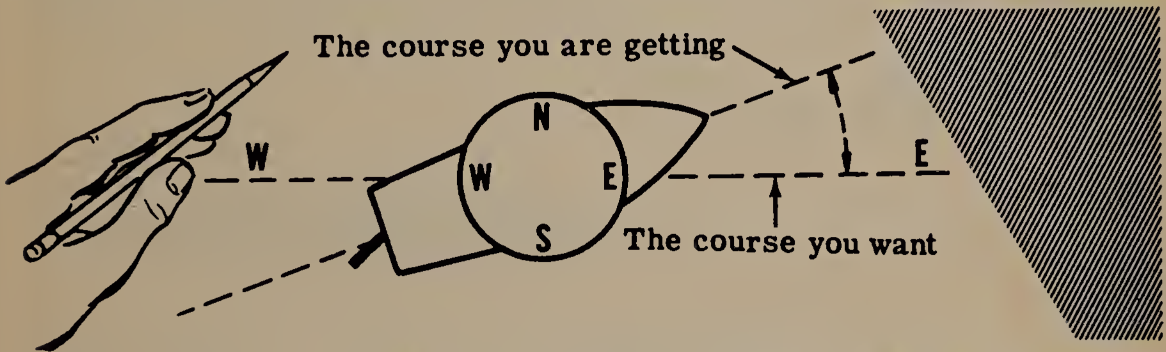


TIME DELAY IN STEERING CAUSES SHIP TO OSCILLATE ABOUT DESIRED COURSE

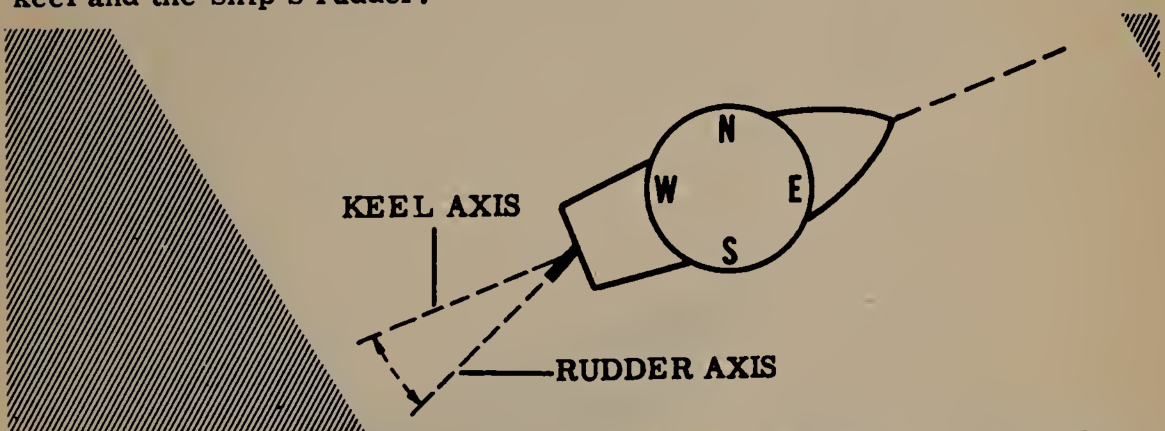
Factors That the Servo Must Consider

The main fault of the automatic steering system is that it does not have continuous control over the ship's rudder. It only knows in which direction to turn the rudder in order to correct an error. It does not know how fast it has to turn the rudder and when it should stop turning the rudder in order to bring the ship right on course without any overcorrection or undercorrection. In other words, this automatic steering servo lacks the judgment of the helmsman.

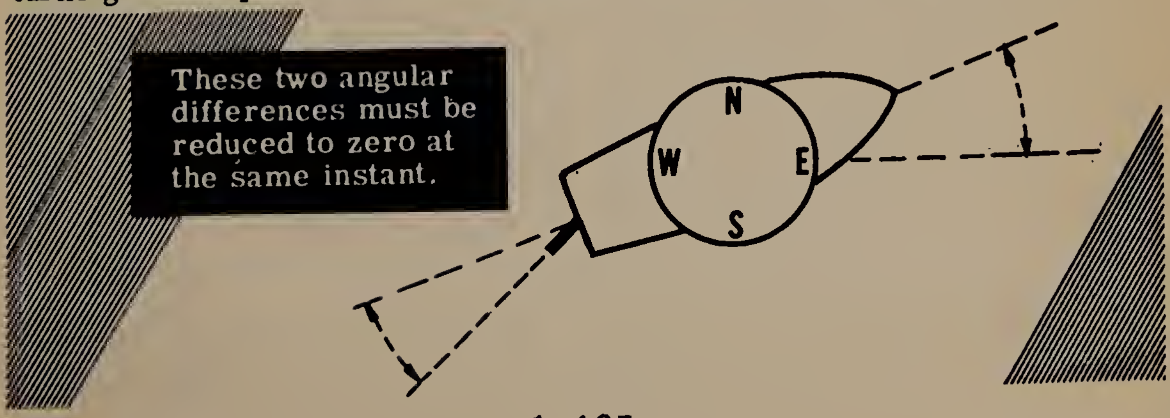
The helmsman takes into consideration the angular difference between the present ship's course and the desired ship's course.



He also takes into consideration the angular difference between the ship's keel and the ship's rudder.



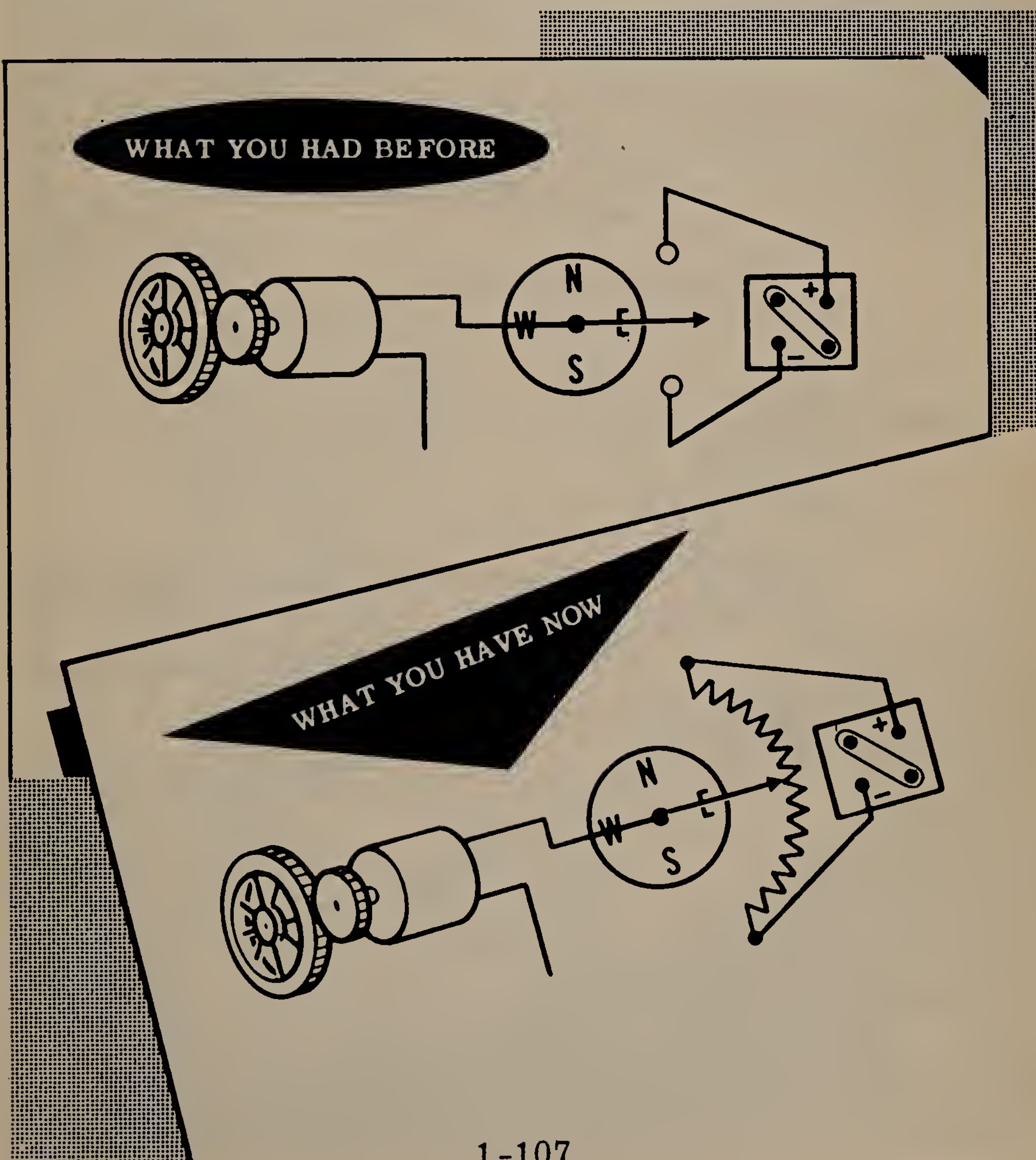
He then uses his judgment and turns the steering wheel so as to reduce each of the above two differences to zero at the same instant—thus returning the ship to its desired course.



Replacing the Reversing Switch with the Compass Potentiometer

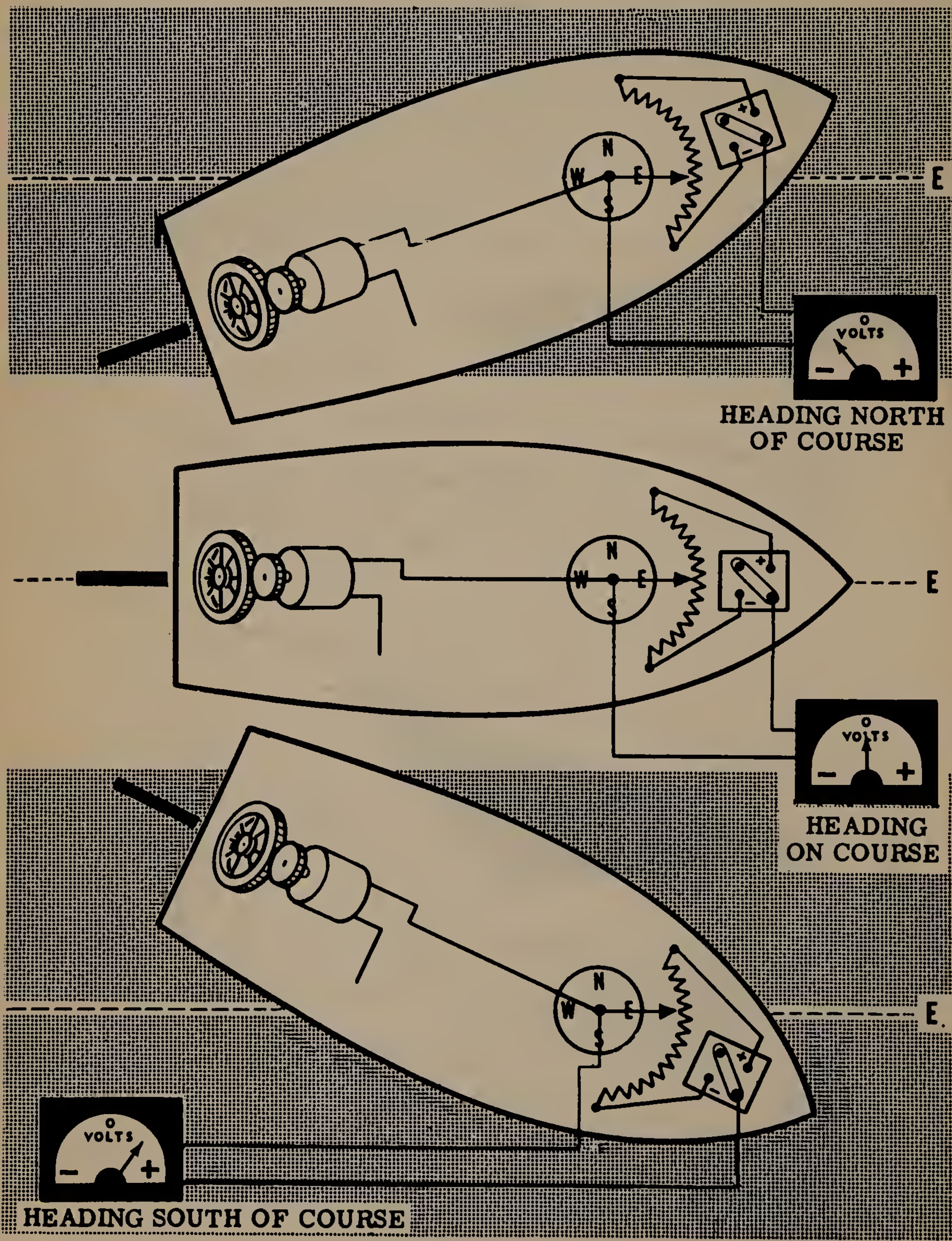
In order for your automatic steering system to operate with the judgment of the helmsman, it must have a means of measuring and acting upon the differences described in the previous section. A good mechanic could work out a mechanical system to do this. However, let's do it electrically, which is the economical way to do it.

The first difference you want to measure is the angular difference between the ship's keel and the ship's course. You know that, if you connect a potentiometer across a voltage source, you can get any voltage difference from zero volts to the maximum source voltage across either end of the sliding arm just by moving the sliding arm to the proper position. If you replace the switch in your old steering system with a potentiometer and if you disconnect the motor from the battery center tap, you have this:



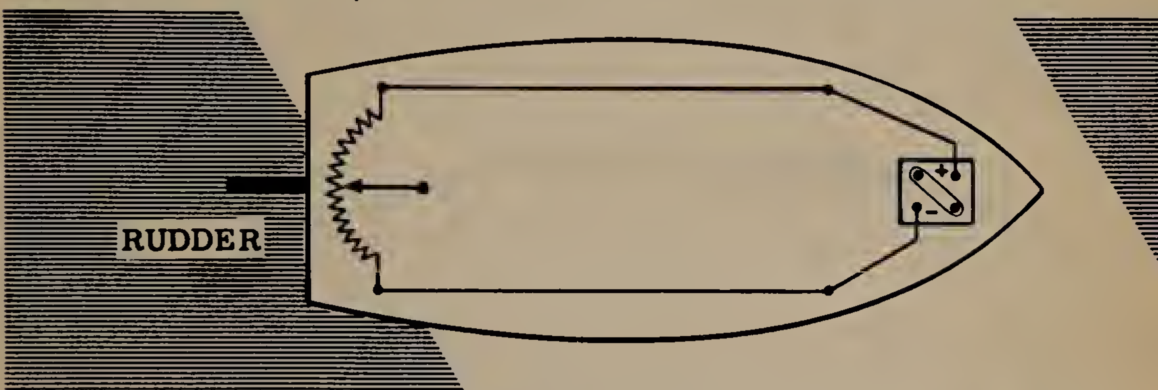
Measuring Angular Difference

If you connect a voltmeter from the potentiometer slider to the battery center tap, you will get a voltage reading which will be proportional to the difference in degrees between the desired course and the present course. This is a measure of what is happening, and you want to reduce this difference to zero degrees.

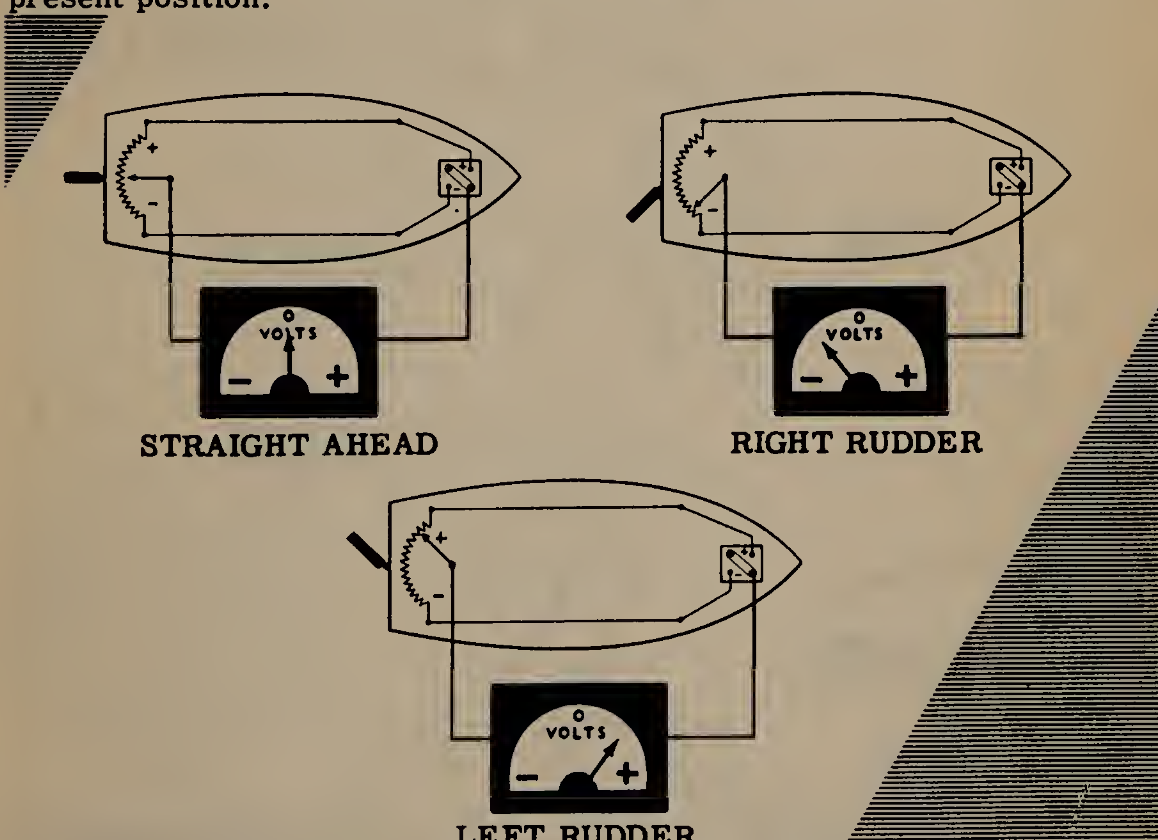


Measuring Angular Difference (continued)

The next thing you want to measure is the difference in angle between the ship's keel and the ship's rudder. The easiest way to measure this angle is with a potentiometer whose sliding arm is connected to the ship's rudder as shown here:



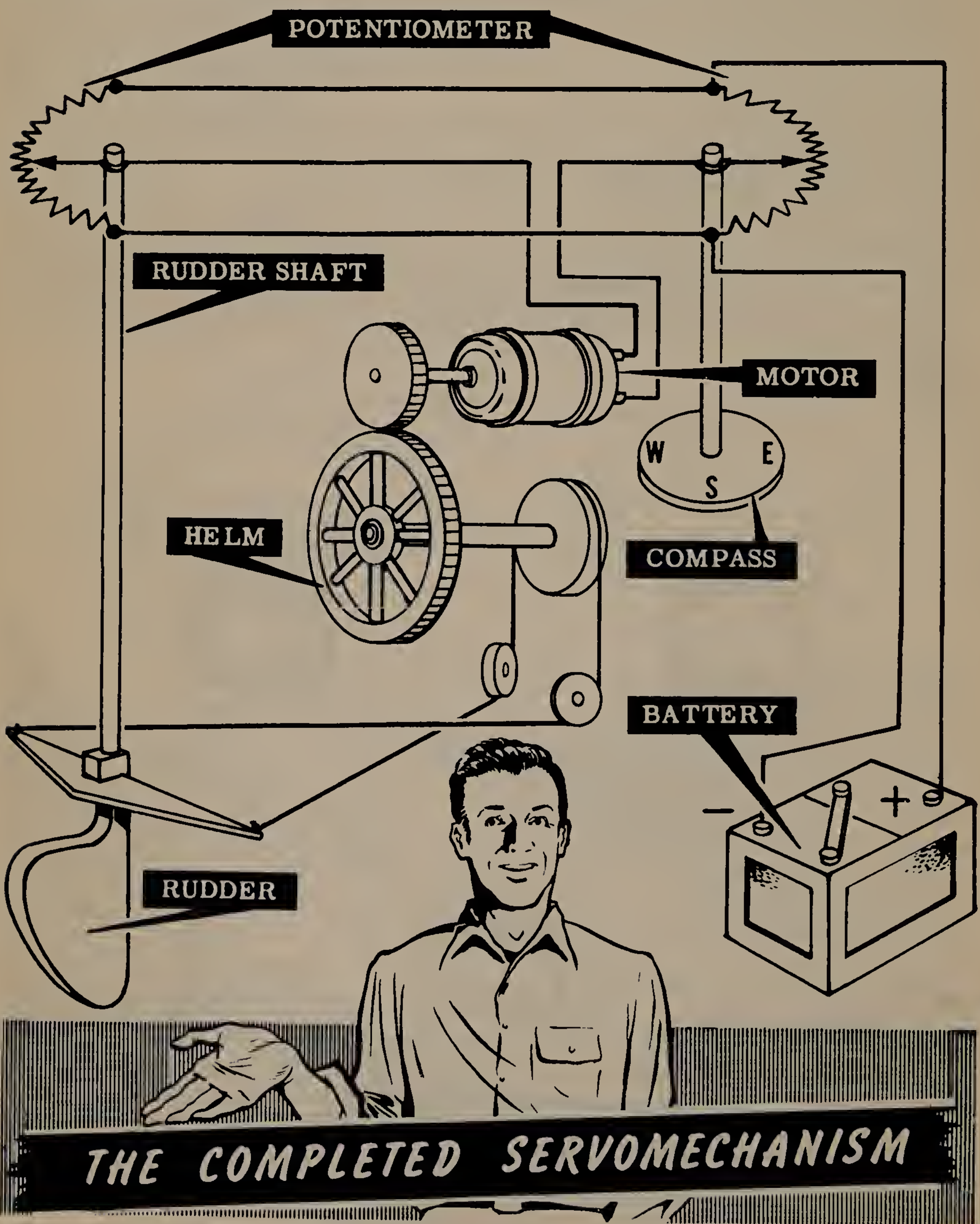
If you connect a voltmeter from the potentiometer slider to the battery center tap, you will get a voltage reading which will be proportional to the difference in angle between the ship's keel and the ship's rudder. This is a measure of what is going to happen if the rudder remains in its present position.



You now have two voltages—one tells you the position of the ship with respect to the desired course, the other tells you the position of the rudder relative to the keel. What you want to do is to act in accordance with the difference between these two voltages. You will then act to keep this difference as small as possible, while also reducing both voltages to zero at the same instant.

The Completed Servomechanism

Since a voltage difference arises across the two potentiometer sliding arms whenever the ship goes off course and since this voltage difference is directly related to the amount of course error, you can use this voltage difference to drive your steering mechanism motor so as to correct the original error in course. Connect your steering wheel motor across the two potentiometer sliding arms. Your continuous control automatic steering system—or servomechanism—is now complete!

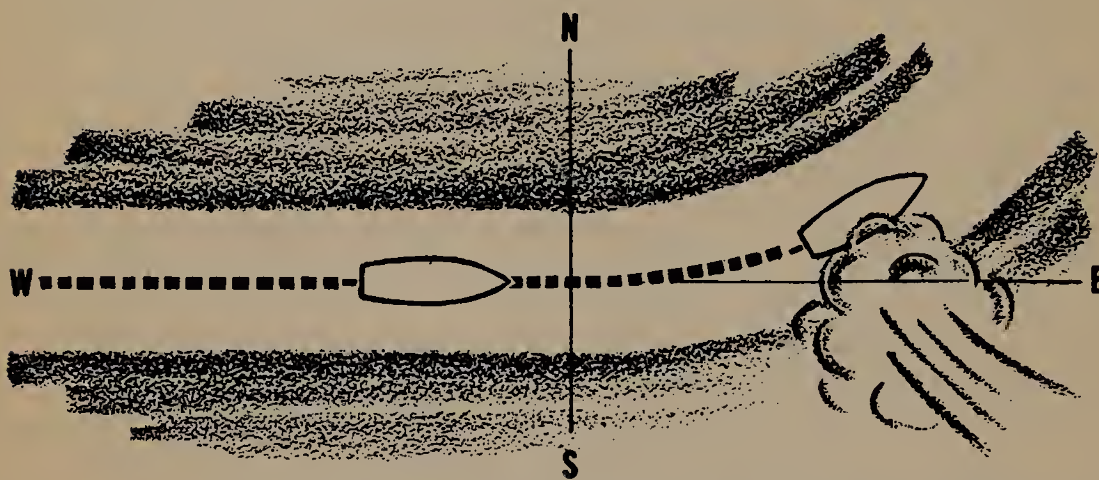


SEEING HOW YOUR SERVO WORKS

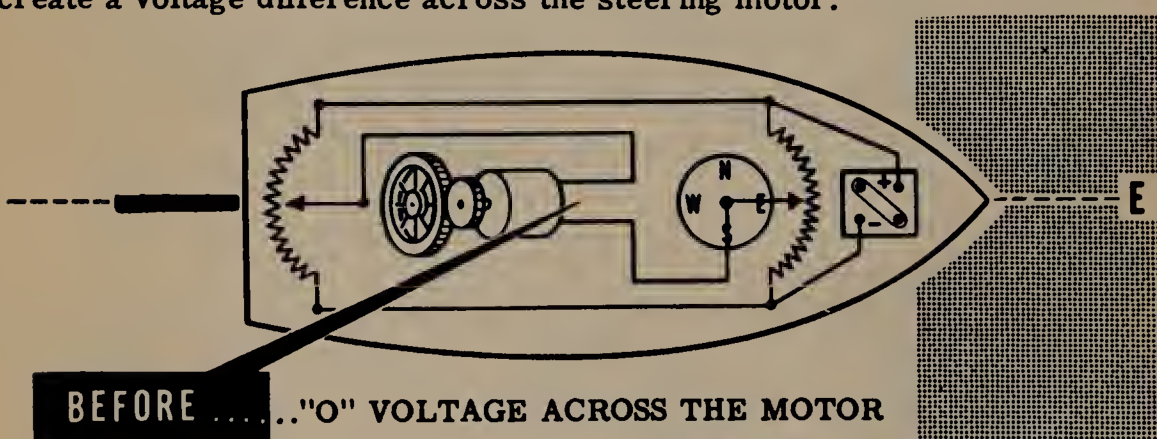
Ship Deviates Off Course

Now that your steering servomechanism is complete, let's see how it works.

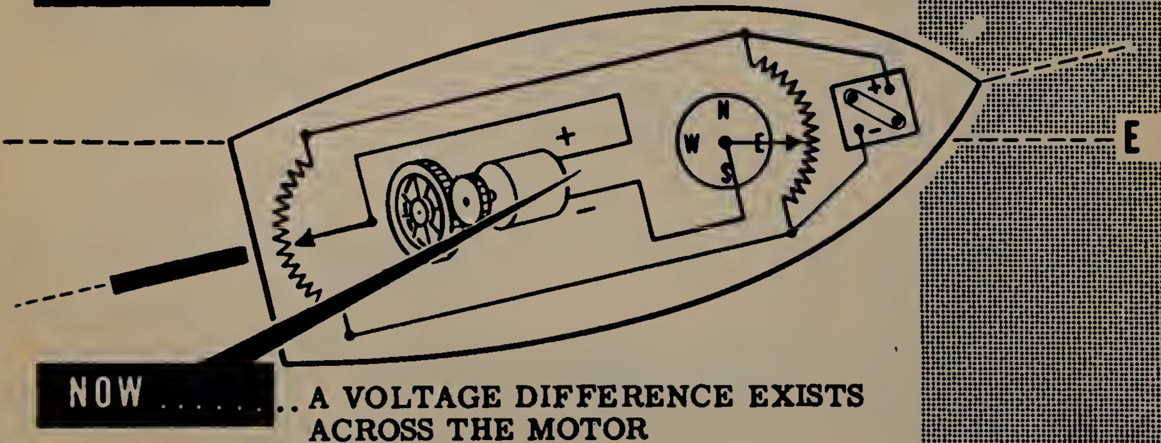
Your ship is running along on a straight course due East when suddenly a powerful gust of wind turns it toward the North.



The compass needle potentiometer arm remains pointed to the East, but since the ship, and hence the potentiometer, turns under it, the potentiometer arm moves away from its center position. The result of this is to create a voltage difference across the steering motor.



BEFORE ......"O" VOLTAGE ACROSS THE MOTOR

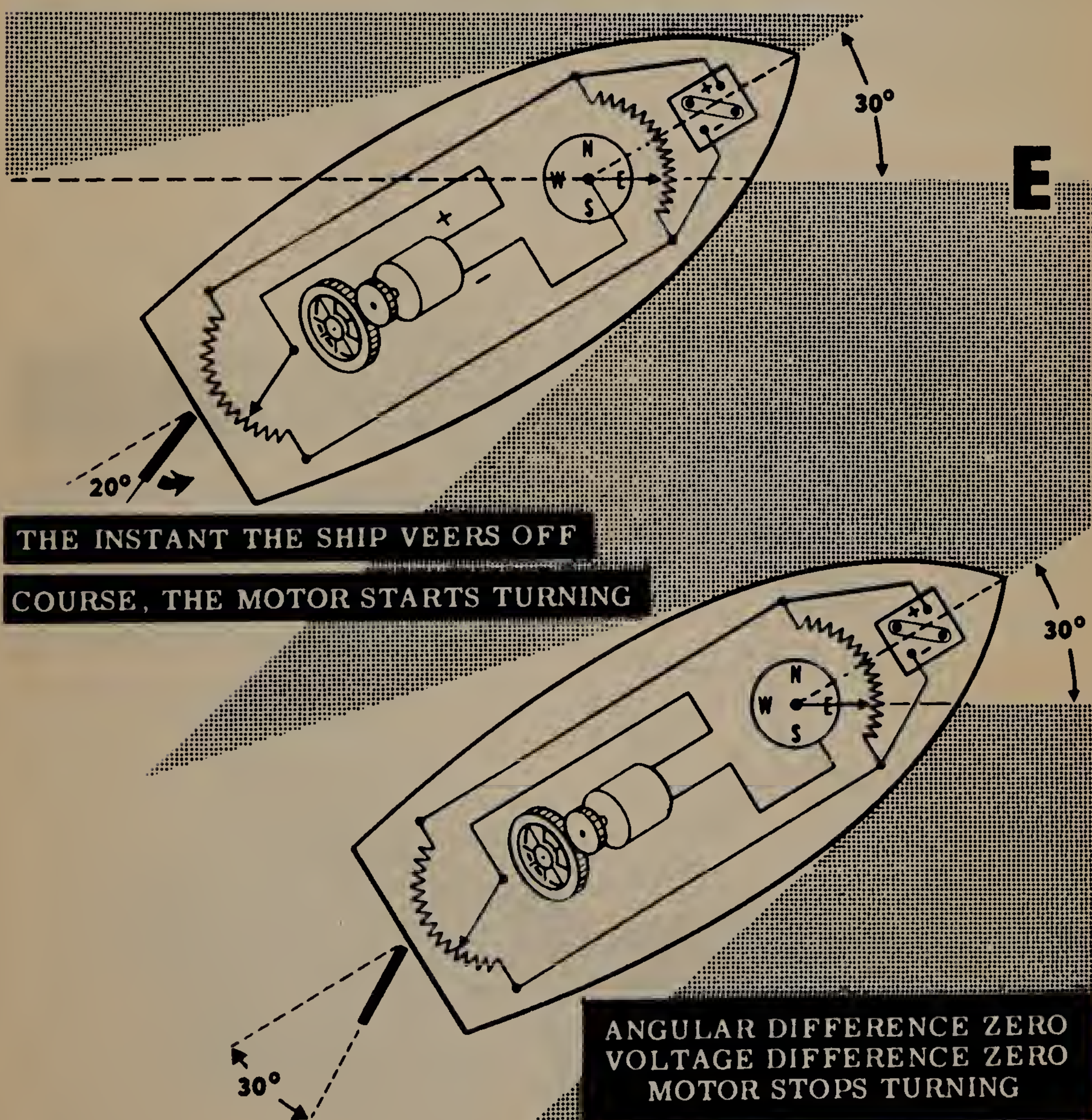


NOW ....A VOLTAGE DIFFERENCE EXISTS ACROSS THE MOTOR

Servo Turns Rudder

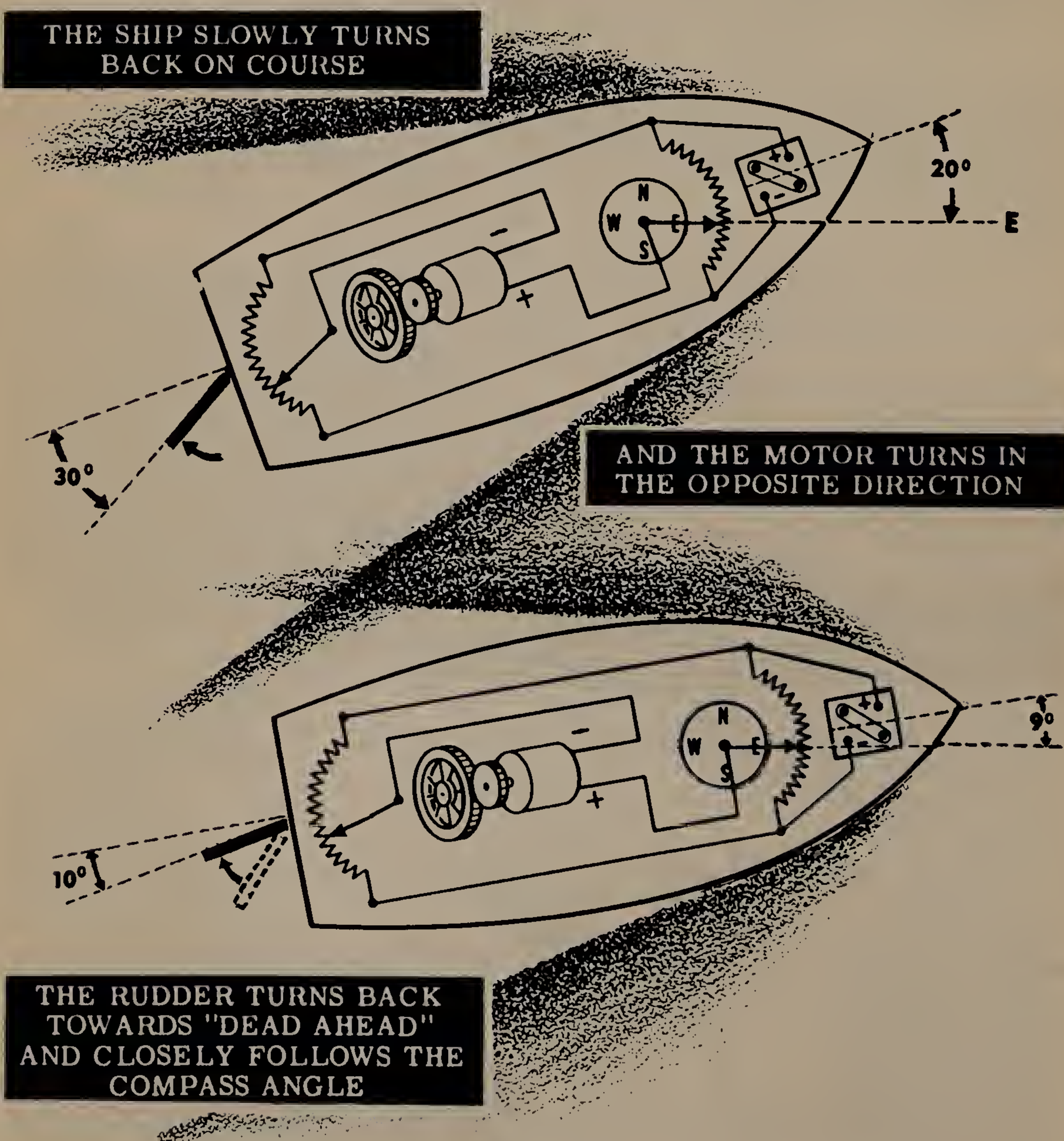
This voltage difference builds up very rapidly since the outside forces turning the ship are very powerful in this case. This rapidly increasing voltage difference makes the motor spin very rapidly. (The servomechanism "knows" that if it doesn't act quickly in this case, the error will become very large.)

The rapidly spinning motor quickly spins the steering wheel and the rudder quickly begins turning so as to correct the error in course. As the ship's rudder begins to turn, it moves the rudder potentiometer sliding arm along with it, decreasing the angular difference between the two potentiometer sliding arms. The decreasing angular difference causes the voltage across the motor to decrease and the motor turns more and more slowly. When the angular difference between the two potentiometer arms is reduced to zero, the motor stops turning.



Ship Turns Back on Course

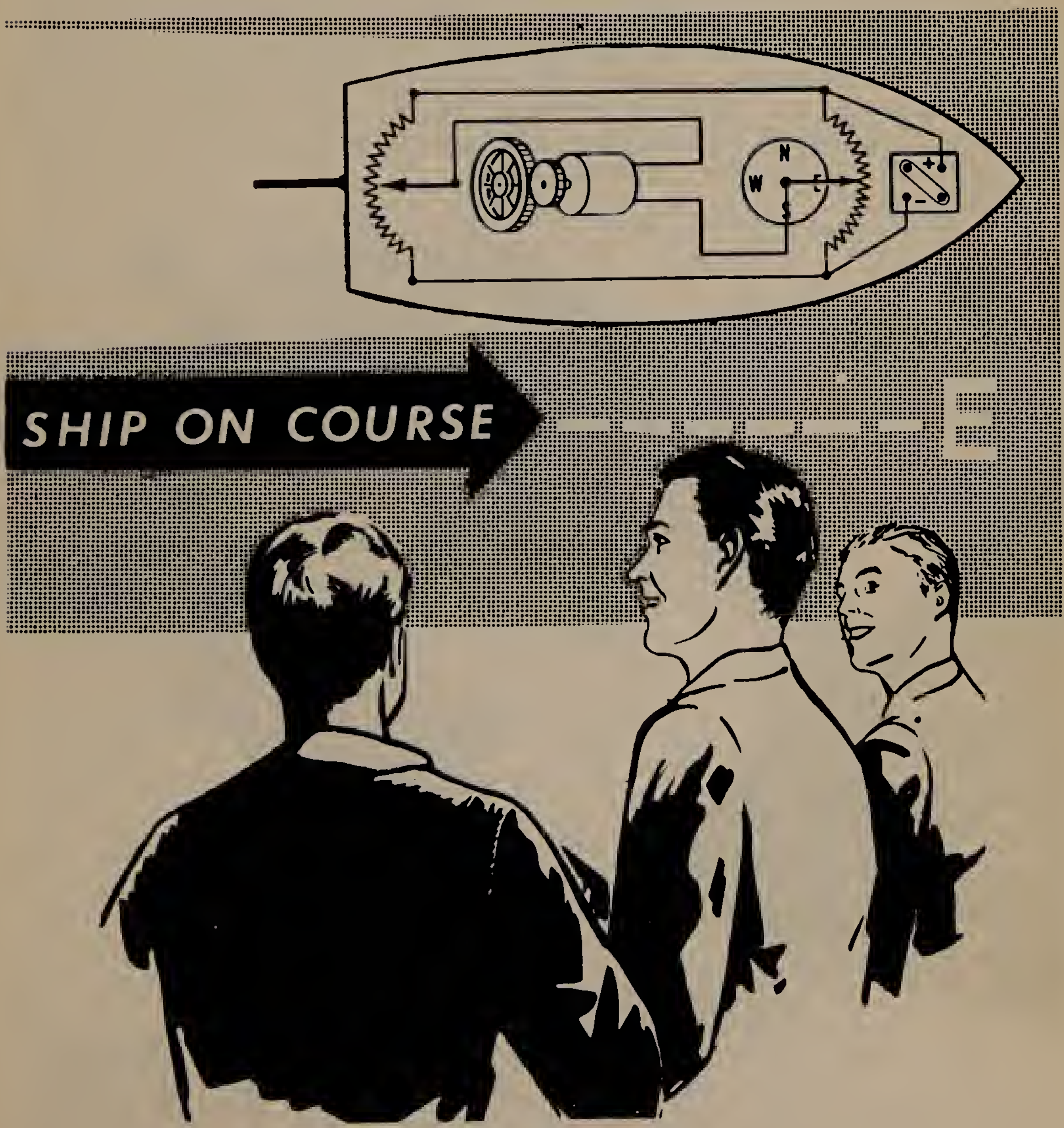
Now the force of the water against the turned rudder causes the ship to swing around slowly back on course. The sliding arm of the compass potentiometer begins to swing back toward its mid-position, causing a new voltage of the opposite polarity to appear across the motor. The motor now rotates in the opposite direction, turning the rudder and the rudder potentiometer back toward the mid-position. The sliding arm of the rudder potentiometer closely follows the sliding arm of the compass potentiometer back toward the mid-position. (The servomechanism knows that it must turn the rudder back to its center position so that the rudder will be centered at the exact time the ship returns to the desired course. Unless the rudder is turned back, the ship will seriously overshoot the desired course.)



Ship "on Course"

As the ship approaches the desired course, the compass potentiometer arm approaches its center position and the motor turns the rudder just the right amount to keep the rudder potentiometer arm approaching its center position at the same speed as the compass potentiometer arm. (The servomechanism "realizes" the importance of easing in the rudder to its center position at the same time that the compass needle reaches the desired bearing.)

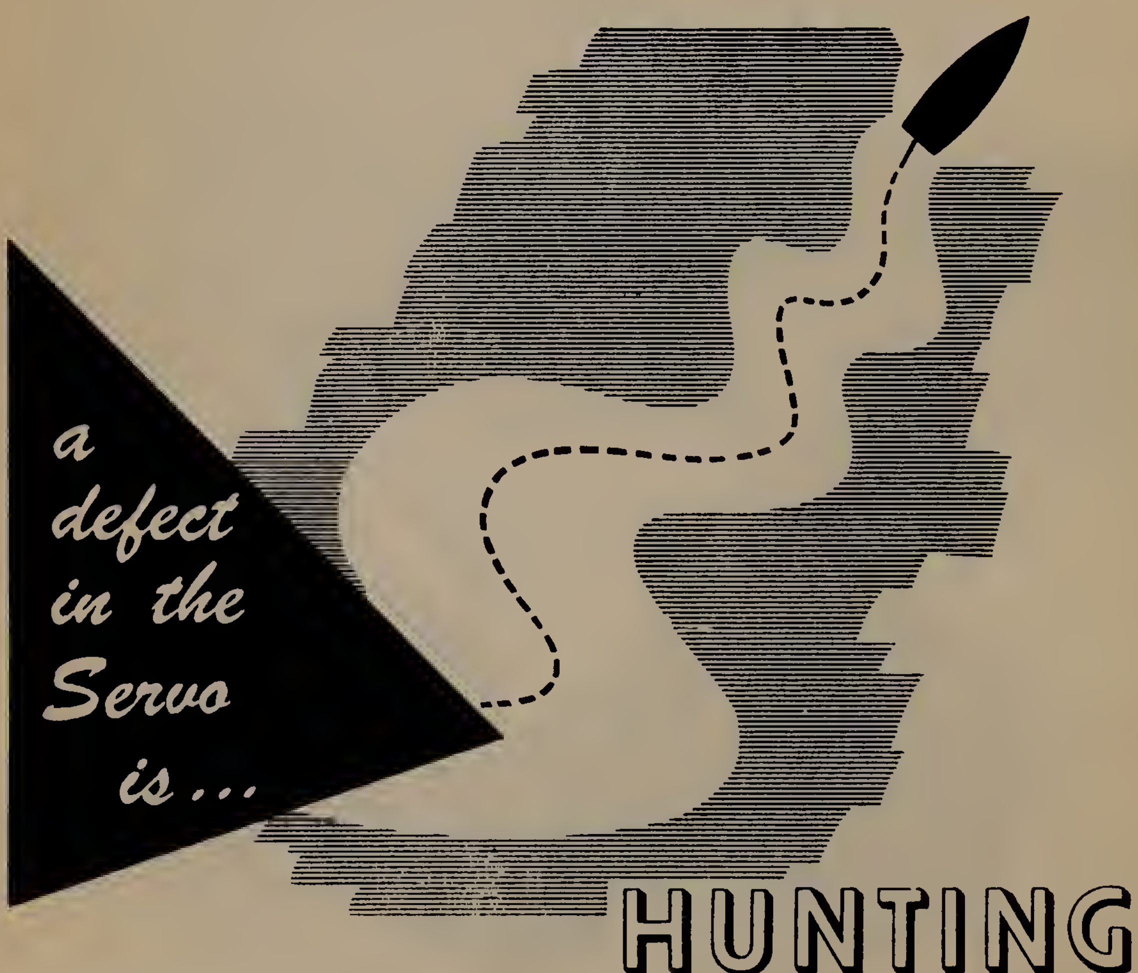
When the compass reaches the desired bearing, the two potentiometer arms become centered at the same time. Since the voltage difference between the two potentiometer center arms is now zero, the voltage across the motor must also be zero. Since the motor has no voltage across it, it stops turning. The ship is on course.



Factors Influencing Servo Operation

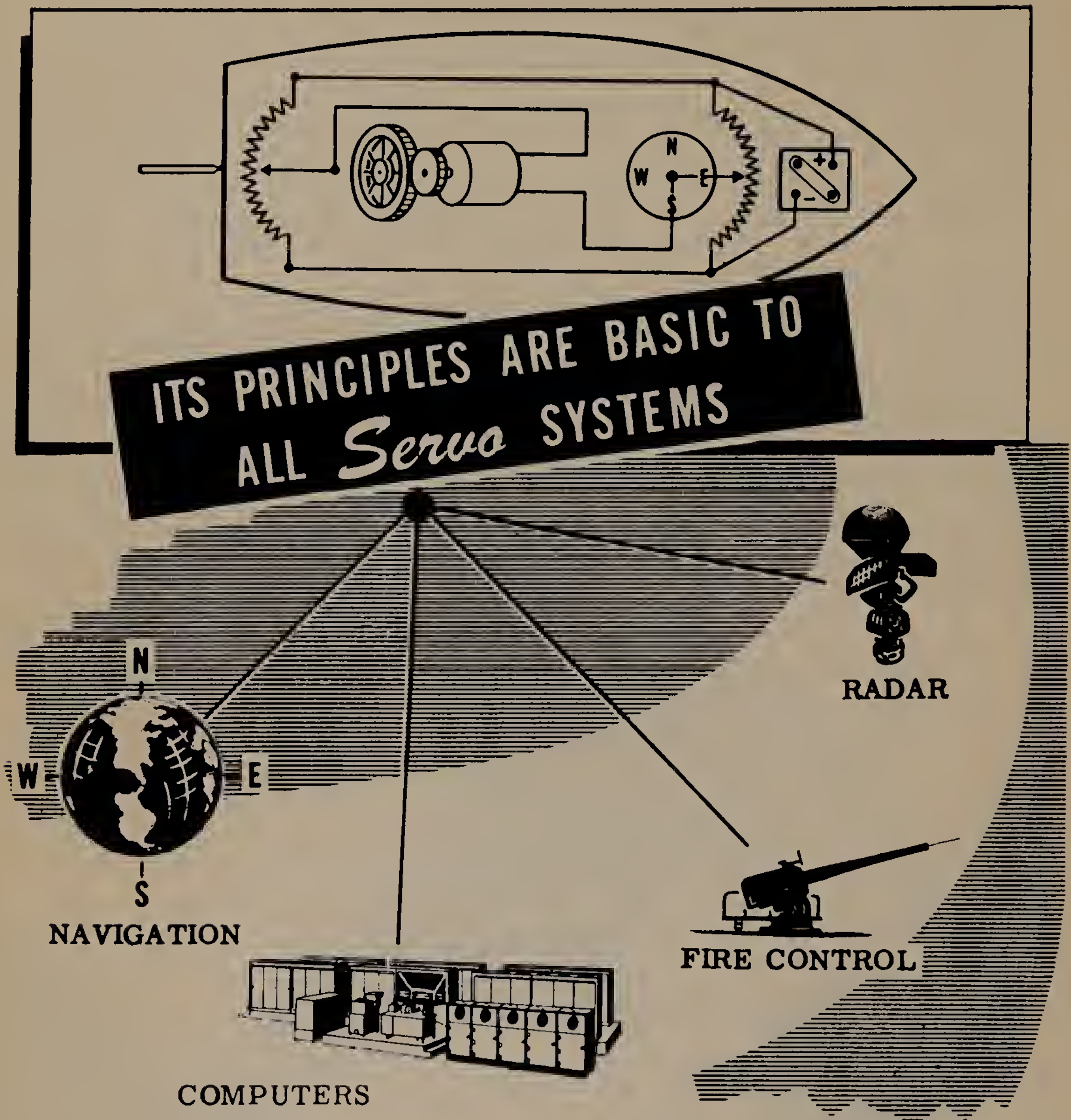
The moment that the ship returns to its desired course is a critical moment. Ignoring further gusts of wind, ocean currents, waves, etc., there are still two factors that tend to make the ship overshoot its desired course. A ship weighs thousands of tons and, when it is turning, it has a terrific amount of momentum which tries to keep it turning. Even under ideal conditions, a short amount of time is required for the effects of the rudder to be felt in the ship's motion. As a result, when the ship is turning back onto its course, the effects of very fine rudder motions may not take effect until after the ship overshoots the desired course.

The other factor is that there are imperfections in the various parts of the servomechanism. For example, the motor may be insensitive to very small voltage differences appearing across its leads. It, therefore, will not turn to correct small errors. This causes the motor to lag behind the voltage appearing across the potentiometer arms. The result of the ship's momentum and the lag in the servomechanism is that the ship may overshoot its course. This overshoot, however, is corrected by the servomechanism in the same manner as the original error. Each overshoot becomes less and less as the ship "hunts" for its desired course and finally finds it. You will find out how this hunting effect can be eliminated when you come to the section on hunting.



YOUR SERVO DEMONSTRATES BASIC CHARACTERISTICS

Has Principles Basic to All Servos



You have just gone through the design of a servomechanism whose function it is to keep a ship on course. Although this servo is theoretically sound, it has too many disadvantages to warrant its use. For example, the manner in which the information about compass and rudder positions is transferred to the potentiometers is rather crude. The use of a motor connected directly across the potentiometer arms is impractical since the potentiometers would have to be gigantic in size to carry the necessary current. Even though many refinements would have to be incorporated in the above servo to make it practical, it has characteristics basic to all servo systems.

For the present, ignore the various impracticalities in your servo and review what you have learned about servomechanisms.

Reviewing the Basic Requirements

Earlier in this discussion of servos, you learned that there were five basic requirements for a system to be an ideal servomechanism. They will be repeated here for review.

1. A servo must be able to accept an order which defines the result that is desired.

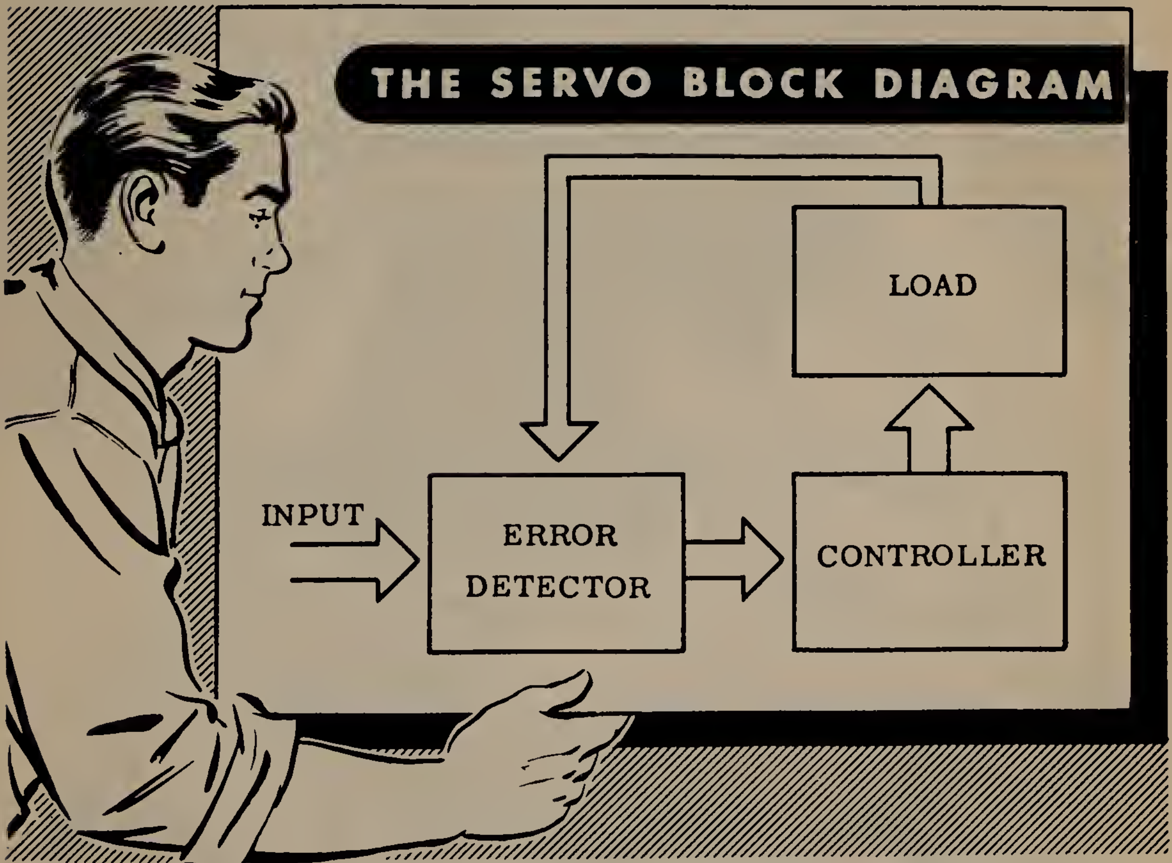
2. A servo must be able to evaluate the existing conditions.

3. A servo must be able to compare the desired result with the existing conditions, obtaining a difference, or error, signal.

4. A servo must be able to issue a correcting order based on the error signal, which will properly change the existing conditions to the desired result.

5. A servo must have the means of carrying out the correcting order.

In order for a servomechanism to meet the five basic requirements outlined above, it must be made up of two major systems—an error detecting system and a controlling system. The load, which is actually the output of the servo, can be considered as part of the controller.



Now suppose you consider your automatic steering servomechanism in terms of its two major systems.

The Error Detecting Component of the Servo

The error detecting system must:

1. Be able to accept an order defining the desired result.
2. Be able to evaluate the existing conditions.
3. Be able to compare the desired result with the existing conditions and determine the error.
4. Be able to issue a correcting order based on the error.

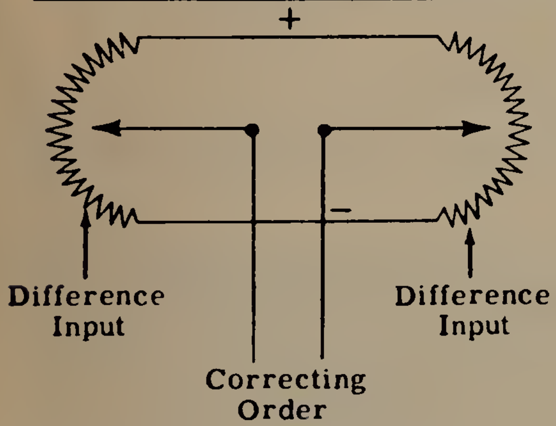
In your automatic steering servo, the error detecting system consists of the rudder and compass potentiometers. The voltage difference developed across the potentiometer center arms is the error signal or correcting order which is applied to the controlling system.

Other Error Detecting Components

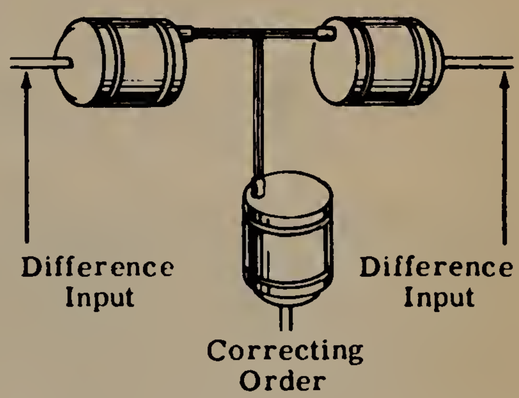
An error detecting system, regardless of the type, must contain all the components necessary to determine the exact difference between the required result and the result actually taking place. This difference must be issued by the error detector as a correcting order in a form that can be used by another system to correct this error. The complexity of the error detecting system depends on the complexity of measuring the various differences involved and of issuing a correcting order.

In your automatic steering servo, the error detecting system consists of the rudder and compass potentiometers. There are many other devices that can be used as error detectors such as gear systems, synchros, pyrometers, air pressure gauges, photo-electric cells, vacuum tube circuits, etc. The type of error detector chosen for a particular job depends upon the nature of the error being measured and the type of relationship existing between the conditions being measured.

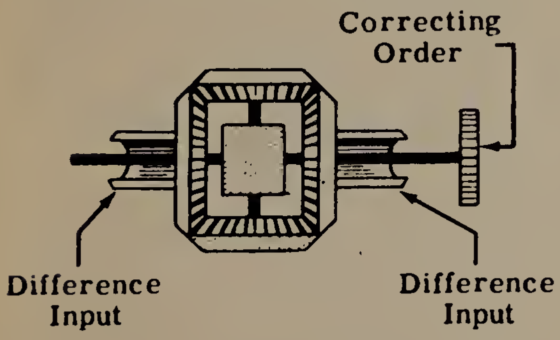
BALANCED POTENTIOMETERS



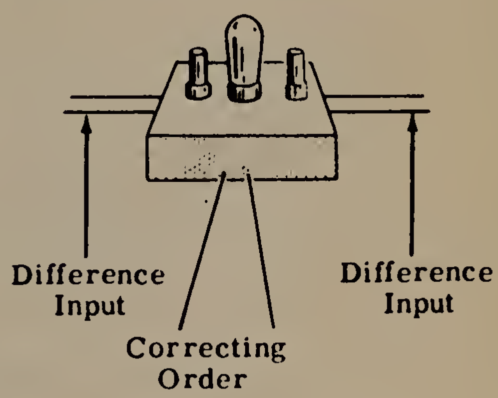
SYNCHRO SYSTEM



GEAR SYSTEM



ELECTRONIC CIRCUIT



The Controller Component of the Servo

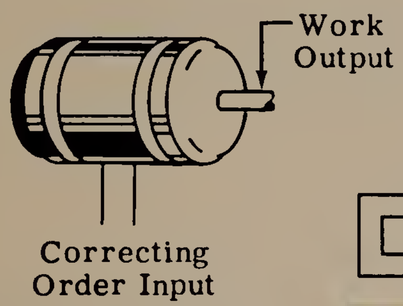
The error correcting or controlling system (generally referred to as the "controlling system," "controller" or "follow-up") is the system that moves various components which affect the job being done. Since the error detecting device puts out the correcting signal, the controller is "told" just what to do, how fast to do it, and when to start and stop. The controller is just a "work horse" that can understand the orders given and transform them into the actual physical work which must be done.

In your steering servomechanism, the controller consisted of a battery, a DC motor, the ship's wheel and the mechanical system tying the ship's wheel to the rudder. In this case, the controller interpreted a correcting order, consisting of a voltage difference, and transformed it into a mechanical force which moved the ship's rudder left or right. The rudder is the output or load.

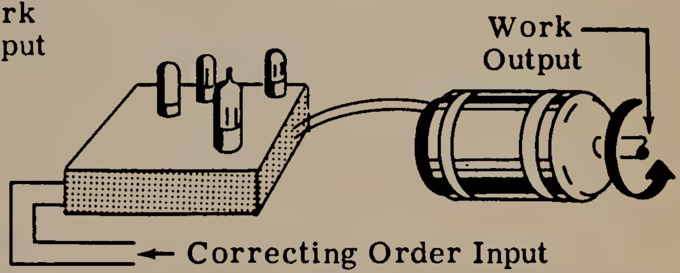
Other Controller Components

Most of the controllers used in equipment contain an electric motor as a driving device. In addition to electric motors, hydraulic and straight gearing devices are also used. Since the error correcting signal put out by the error detector is usually too weak to drive the motor directly, a servo amplifier is placed between the error detector and driving motor. The servo amplifier amplifies the weak error signal so that it becomes strong enough to turn over the driving motor.

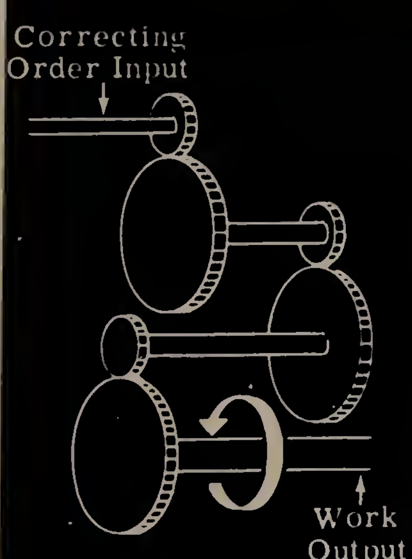
Many types of motors are used for servo work because of the variations in speed, accuracy and horsepower output conditions required by different jobs.



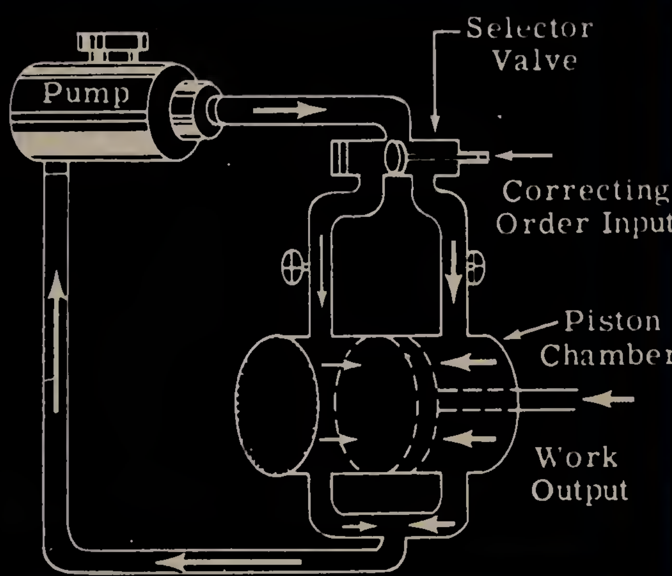
SERVO MOTOR



SERVO MOTOR WITH AMPLIFIER



GEAR SYSTEM

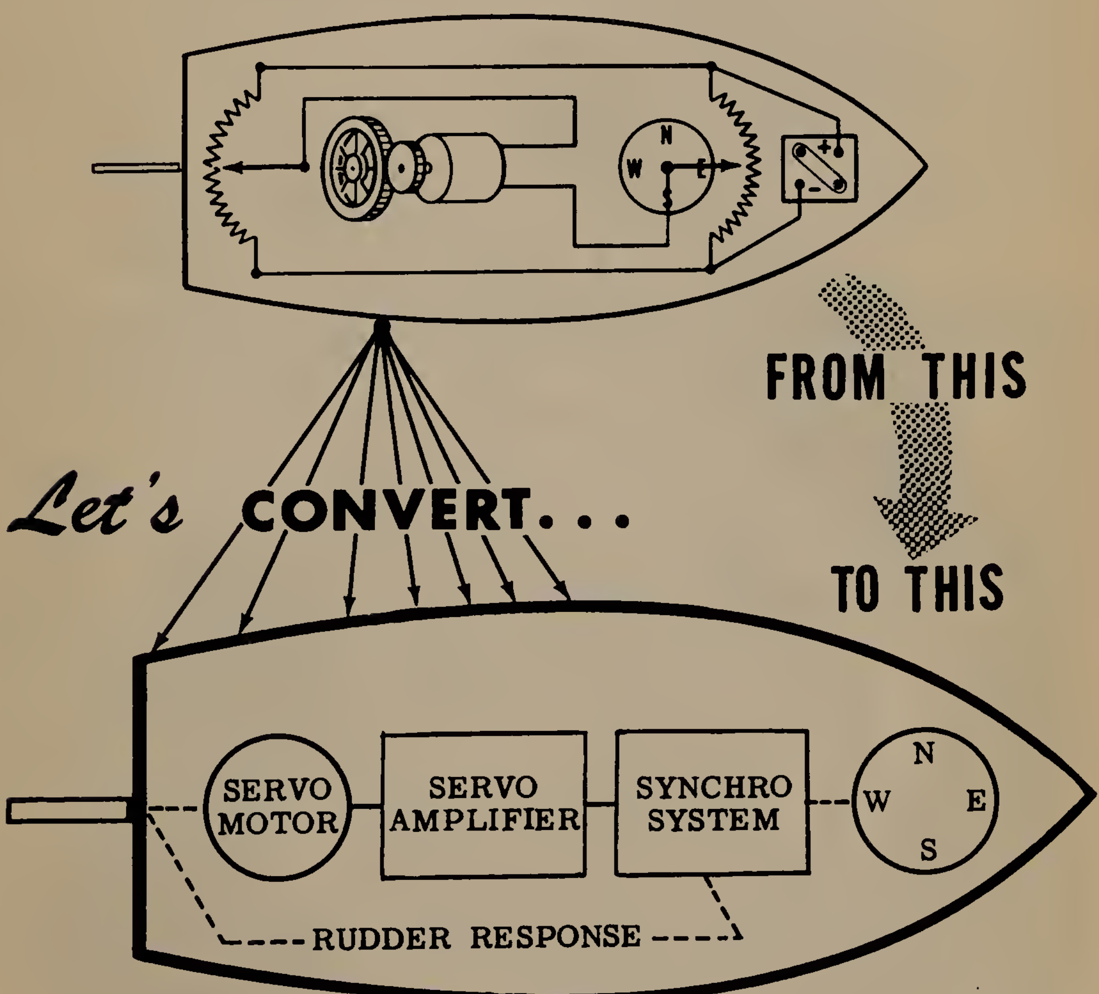


HYDRAULIC SYSTEM

The Advantage of Using Synchros

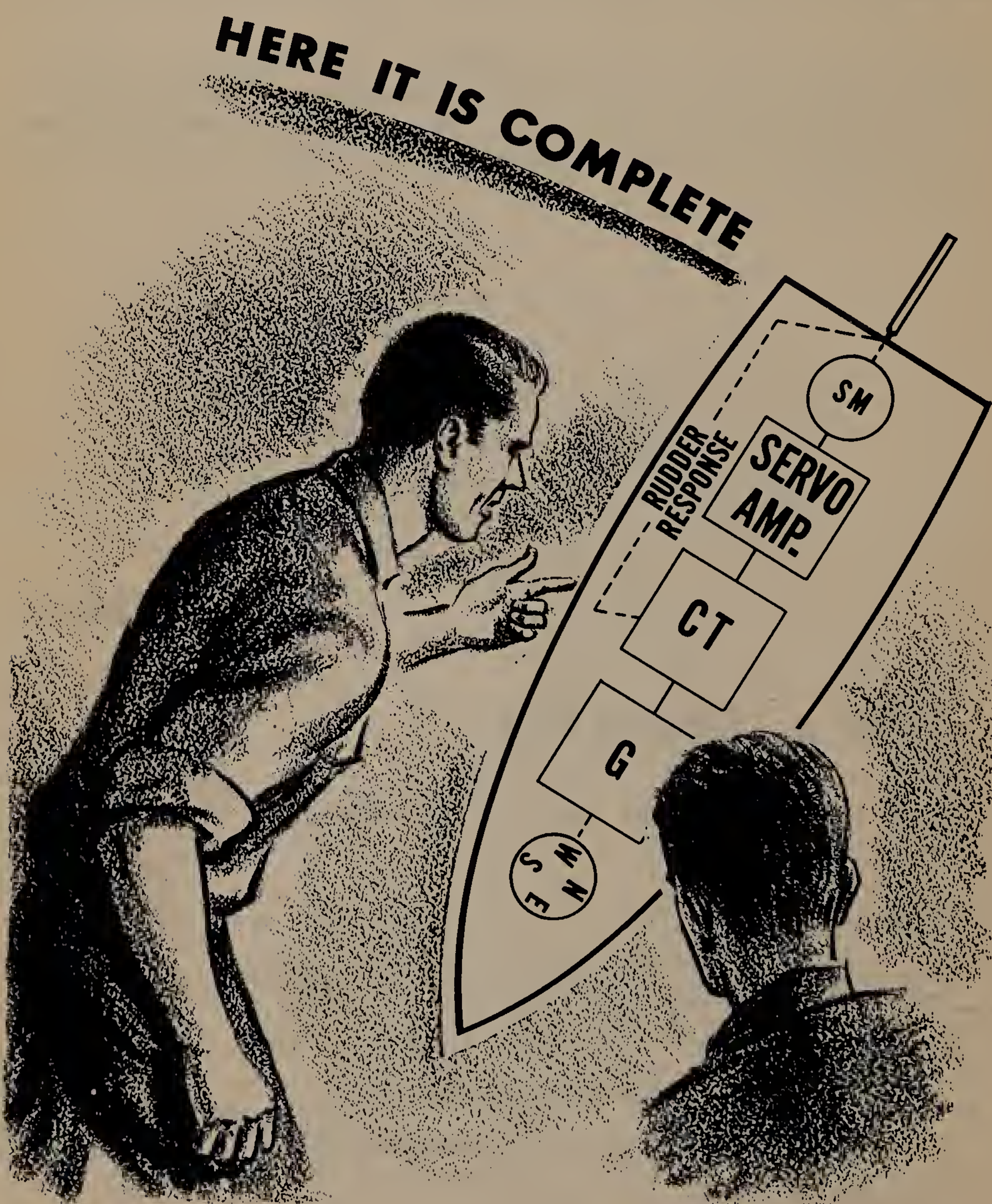
When you designed your automatic steering servo, you used two balanced potentiometers for the error detecting system. Although the servo was theoretically sound, it had a number of disadvantages which made it impractical to use as a working servomechanism. The potentiometers could not handle the large currents required by the driving motor without burning up. The entire system was insensitive to small errors and would not correct for them. Also, it is not very easy to couple the shaft of a potentiometer to the rotating dial of a compass. Finally, the compass dial does not develop the torque required to turn the potentiometer shaft.

It would be possible to improve the automatic steering servo by substituting a synchro system in place of the balanced potentiometers, and a servo amplifier and motor in place of the present motor and battery supply. This would bring the servo more in line with the systems used in actual practice.



Replacing the Balanced Potentiometers, Battery and Motor

The input in the old system consisted of the rotating compass dial and the compass potentiometer. In place of the potentiometer you can substitute a synchro generator whose rotor shaft is mechanically coupled to the rotating compass dial. In place of the potentiometer which constituted the error detecting system, you can substitute a synchro control transformer; and in place of the battery and DC motor, you can substitute a servo amplifier and follow-up motor. Your conversion to a servo system using synchros is now complete.

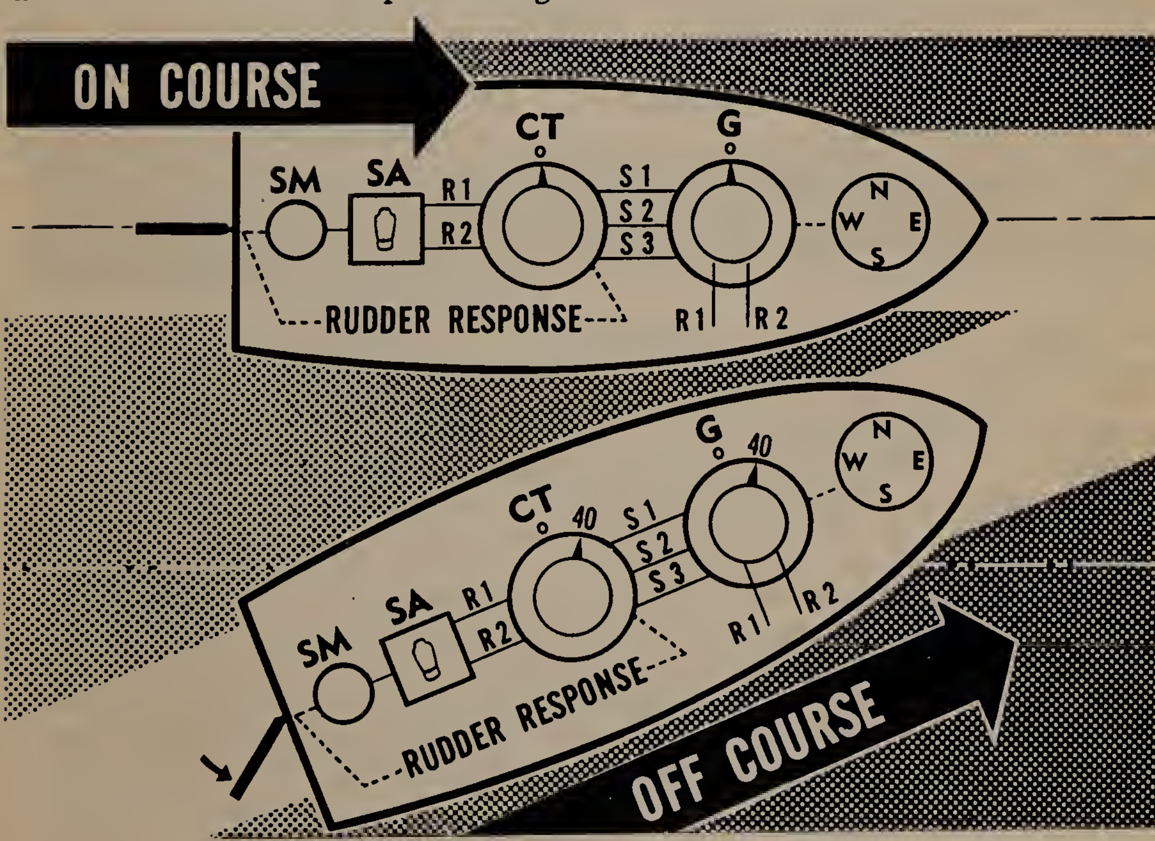


Ship Deviates off Course

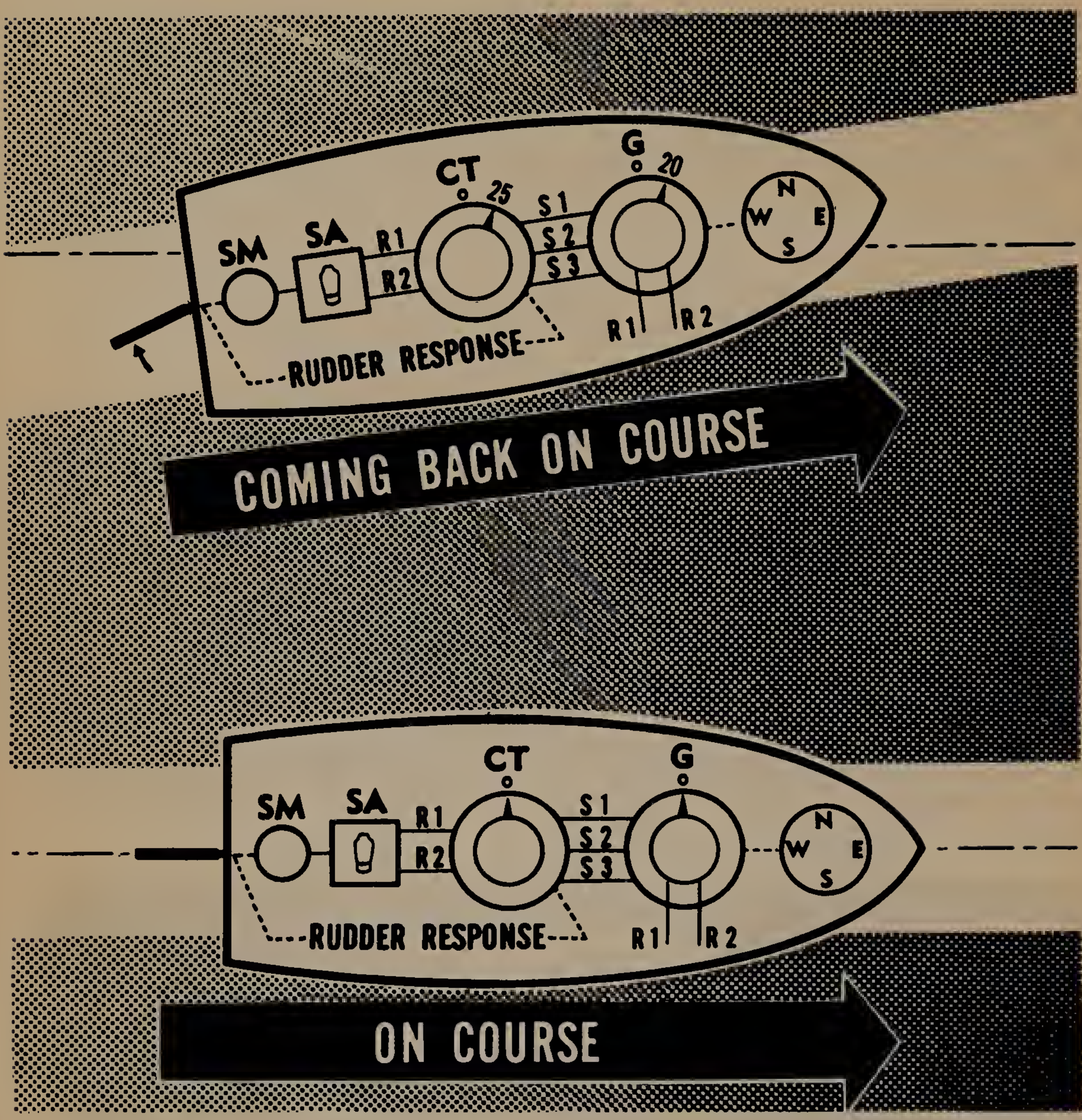
Suppose you analyze the operation of your converted servo on the basis of your knowledge of synchro system operation. Refer to a previous section "The Control Transformer" for a review of the operation of a synchro system using a CT.

When the ship is on course, the rudder is resting at its center position and the ship's keel is pointing due East—the designated course. The synchro system would then be so set up that the rotors of the G and CT are positioned at zero degrees. Since the CT rotor is at zero degrees, there is no voltage developed across the rotor. As a result the servo amplifier has nothing to amplify and the servo motor does not turn. The rudder consequently remains centered.

When the ship deviates off course due to either wind or current changes, the compass dial will rotate relative to the ship's keel. Since the rotor of the G is mechanically coupled to the compass dial, it will also rotate, causing the resultant magnetic field in the stators of the G and CT to rotate by the same amount. The magnetic field in the stator of the CT now cuts through the windings of the rotor and a voltage is developed across the rotor output. This voltage is amplified by the servo amplifier and is applied to the servo motor. The servo motor turns and causes the rudder to rotate in such a direction as to make the ship come back on course. The servo motor is also mechanically coupled to the rotor of the CT, which it will turn so that the CT rotor approaches correspondence with the generator rotor. As the CT rotor approaches correspondence, the error signal output from the CT decreases in magnitude and the servo motor slows down. When the CT rotor is in correspondence, the error signal is zero and the servo motor stops rotating.



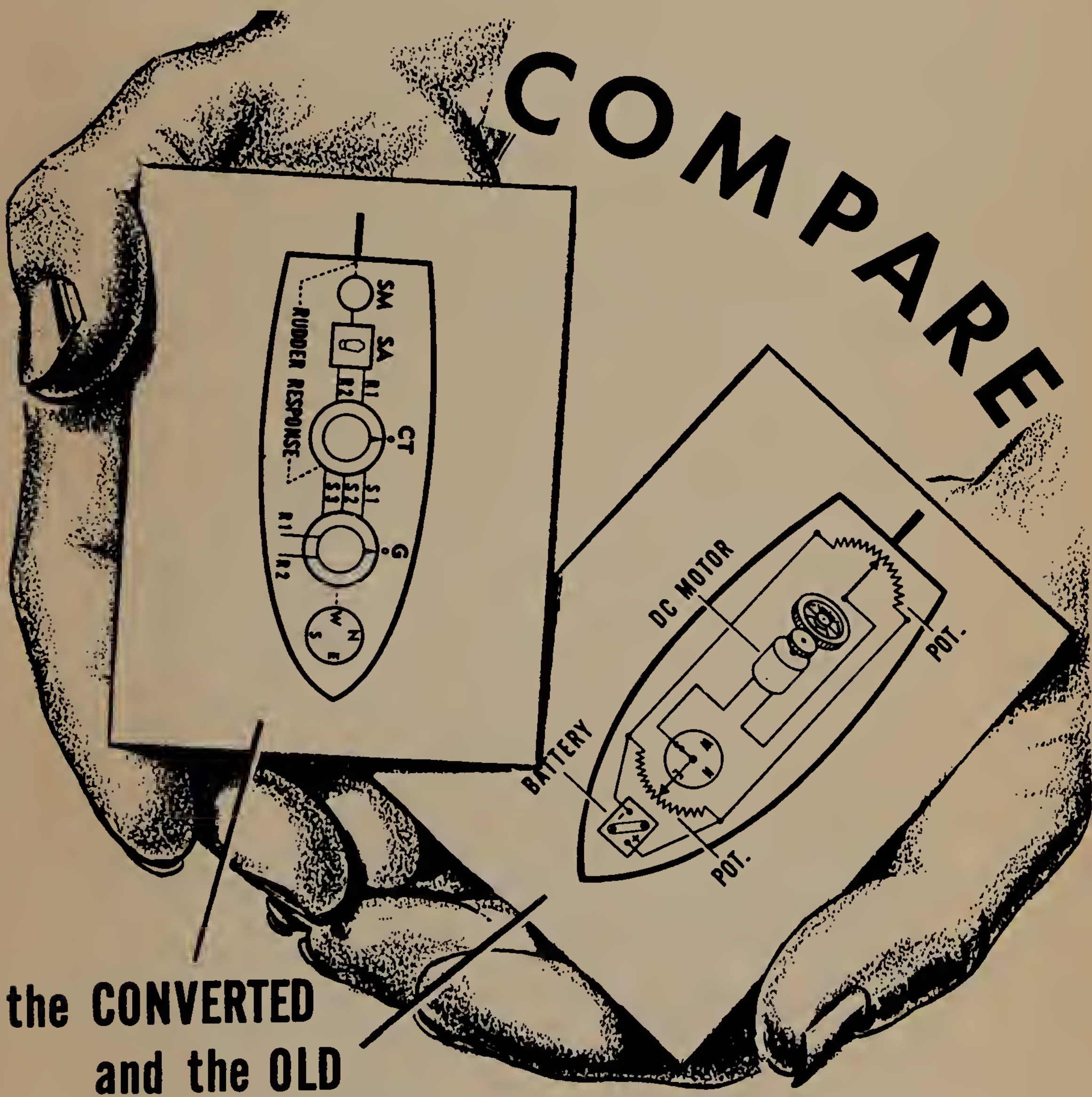
Ship Turns Back on Course



The turning action of the rudder begins to take effect and the ship swings back on course. The compass dial now will rotate toward its original position, turning the rotor of the G back toward zero degrees. The resultant magnetic field in the stators of the G and CT also rotate back toward zero degrees. The rotors of the G and CT are no longer in correspondence, and the resultant magnetic field in the stator of the CT cuts through the windings of the CT rotor in the opposite direction to that which it did previously. A voltage is generated across the CT rotor which now is 180 degrees out of phase with the previously developed voltage. The servo amplifier amplifies this voltage and applies it to the servo motor. The servo motor rotates in the opposite direction, turning the rudder towards its center position and the CT rotor back toward zero degrees. The error signal developed in the rotor of the CT is just enough to keep the servo motor rotating, so that the CT rotor closely follows the rotor of the G back toward zero degrees.

Comparing Your Converted Servo with the Original

As the ship approaches the desired course, the CT rotor approaches correspondence with the rotor of the G, so that the error angle and error signal keep on getting smaller and smaller. When the ship is on course, both rotors reach the zero degree position practically at the same instant and the servo motor stops turning. The ship is once again on course, the rudder is centered and the servo system has accomplished its job of returning the ship to its desired course.

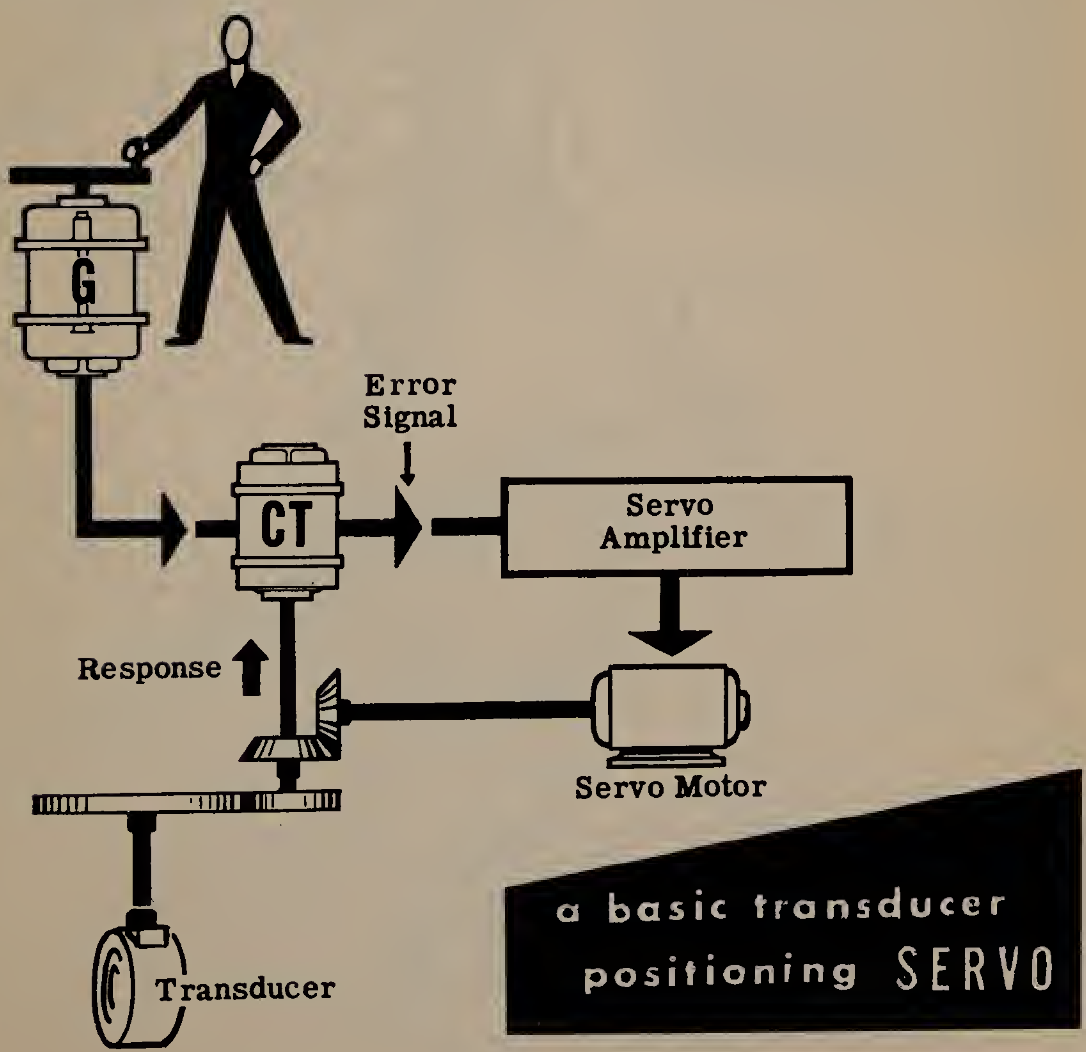


Compare the operation of the converted servo with your original design. You can see that both servos do the job of keeping the ship on course. However, the converted servo will do the job much more efficiently, because the servo amplifier improves the response sensitivity of the servo to small error deviations. Both servos, the original and the converted, are of the positioning type.

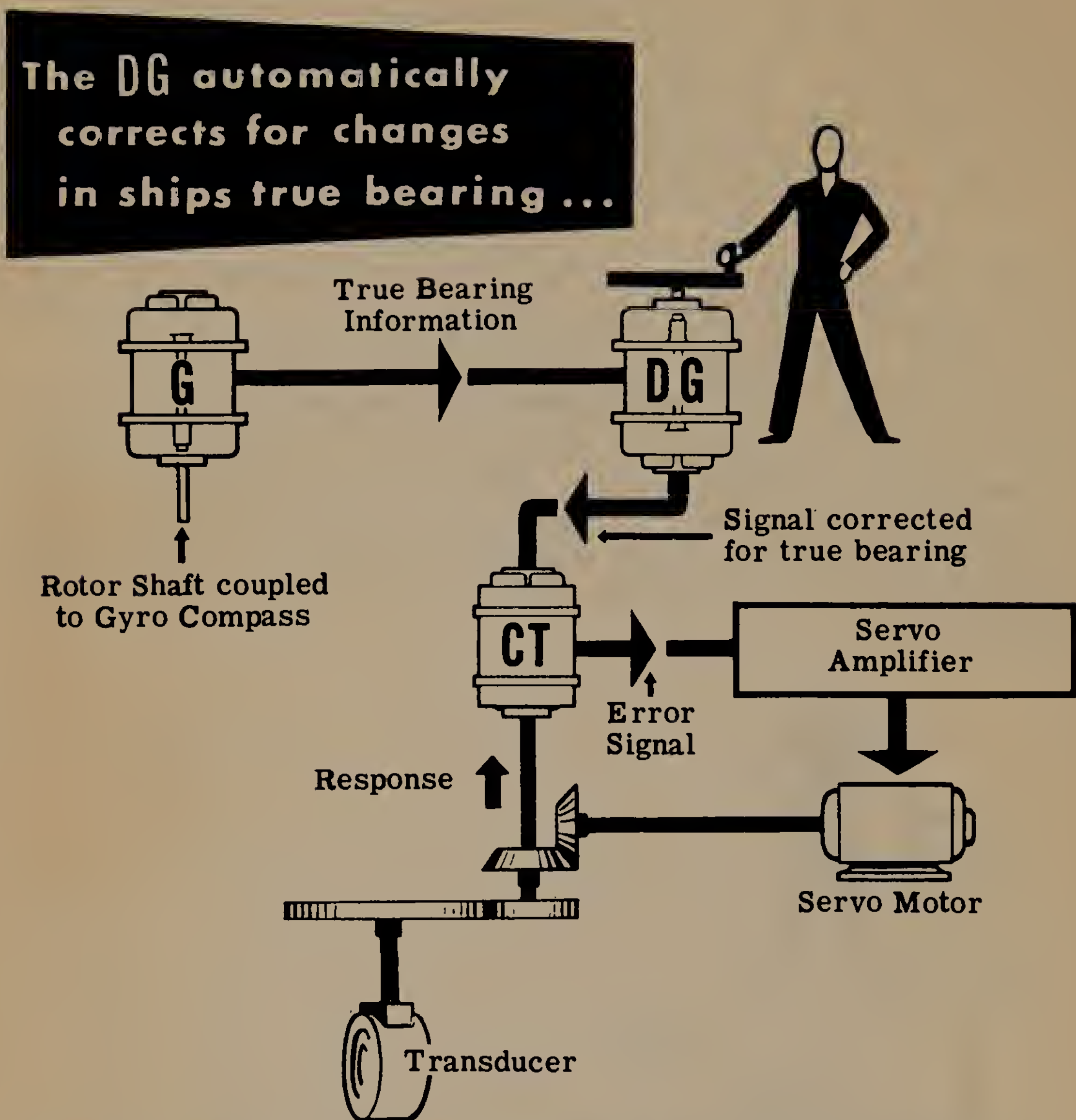
A Block Diagram Analysis

To illustrate another practical servo system, you can analyze the operation of a basic transducer positioning servo such as might be found on a shipboard sonar set. This servo works in exactly the same way as your automatic steering servo. The only difference is that in the automatic steering servo, the initial input is obtained from the wind veering the ship off course, whereas in this servo the initial input is usually put in by a man turning a hand crank.

Originally the servo is set up so that when the transducer is pointing to the bow of the ship, all synchros are zeroed. There would then be no output from the CT and the servo motor would not turn. When the hand crank on the G shaft is turned, the resultant magnetic fields in the synchros rotate, and a voltage is generated across the rotor leads of the CT. This voltage, of a certain phase, is amplified by the servo amplifier and applied to the servo motor. The servo motor rotates in the direction corresponding to the phase of the signal, positioning the load and driving the CT rotor in response, until the CT rotor is again in correspondence with the generator rotor. At this point the error angle is zero and all driving stops. The transducer has been turned through the desired angle and is now in position.



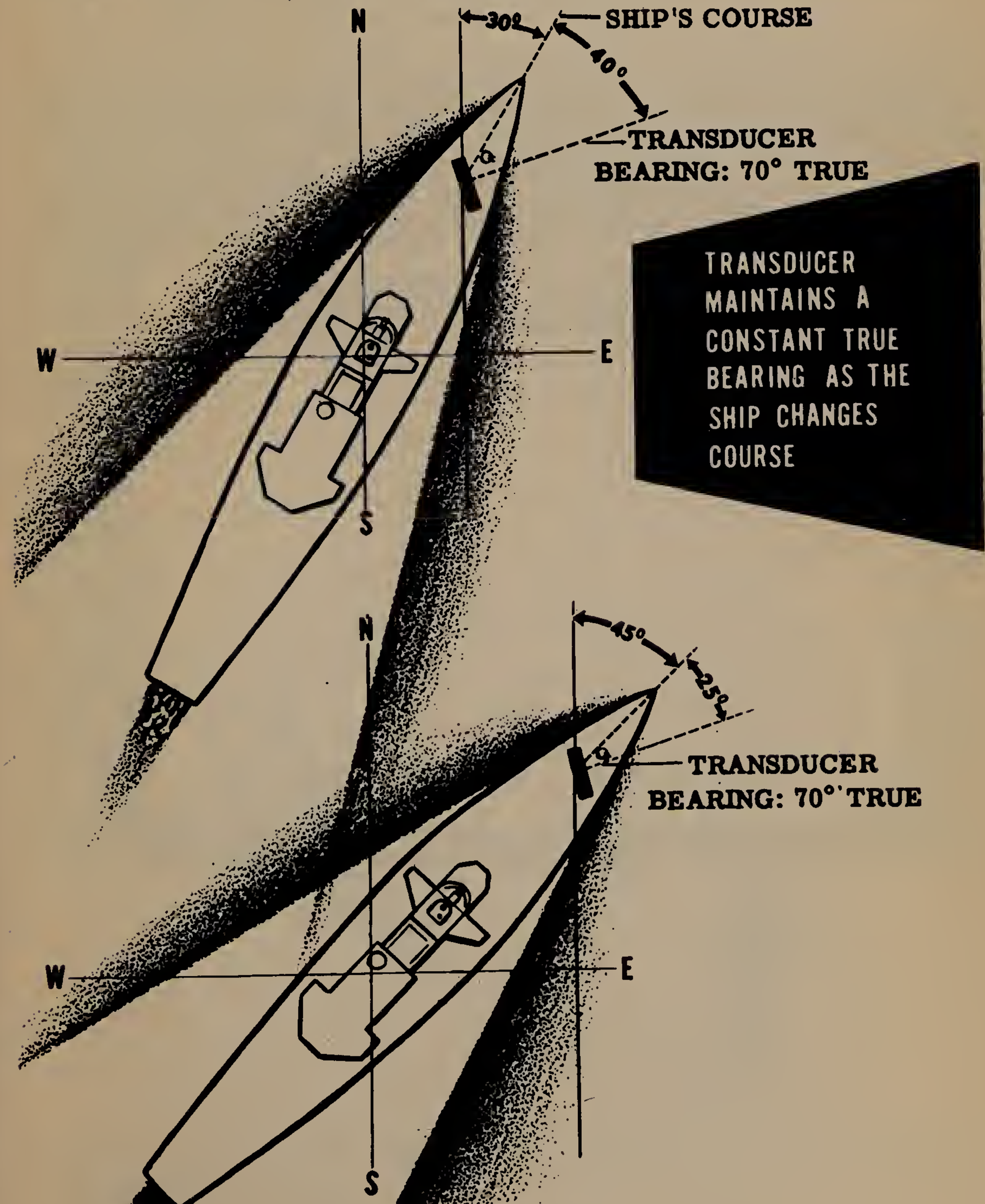
Adding a DG to Correct for Ship's Bearing



A disadvantage of the transducer positioning servo is that it does not take into consideration changes in the ship's course. If the transducer is fixed-trained on an object and the ship's true bearing changes, the transducer will maintain the same relative bearing and will no longer be trained on the object. Of course a correction signal can be fed into the servo by manually turning the hand crank in such a direction as to cause the transducer to train on the object once again. It would be desirable to modify the servo system so that the transducer automatically remains trained on the object regardless of the changes in the ship's true bearing. A way to do this is to replace the synchro generator with a differential generator. The rotor of the DG is electrically connected to the ship's gyro compass synchro and mechanically coupled to the hand crank. The direction of the DG rotor magnetic field can now be varied mechanically by means of the hand crank and electrically by means of a true bearing indication signal from the ship's gyro compass synchro. The block diagram illustrates the modified servo system designed to correct for changes in ship's true bearing.

Adding a DG to Correct for Ship's Bearing (continued)

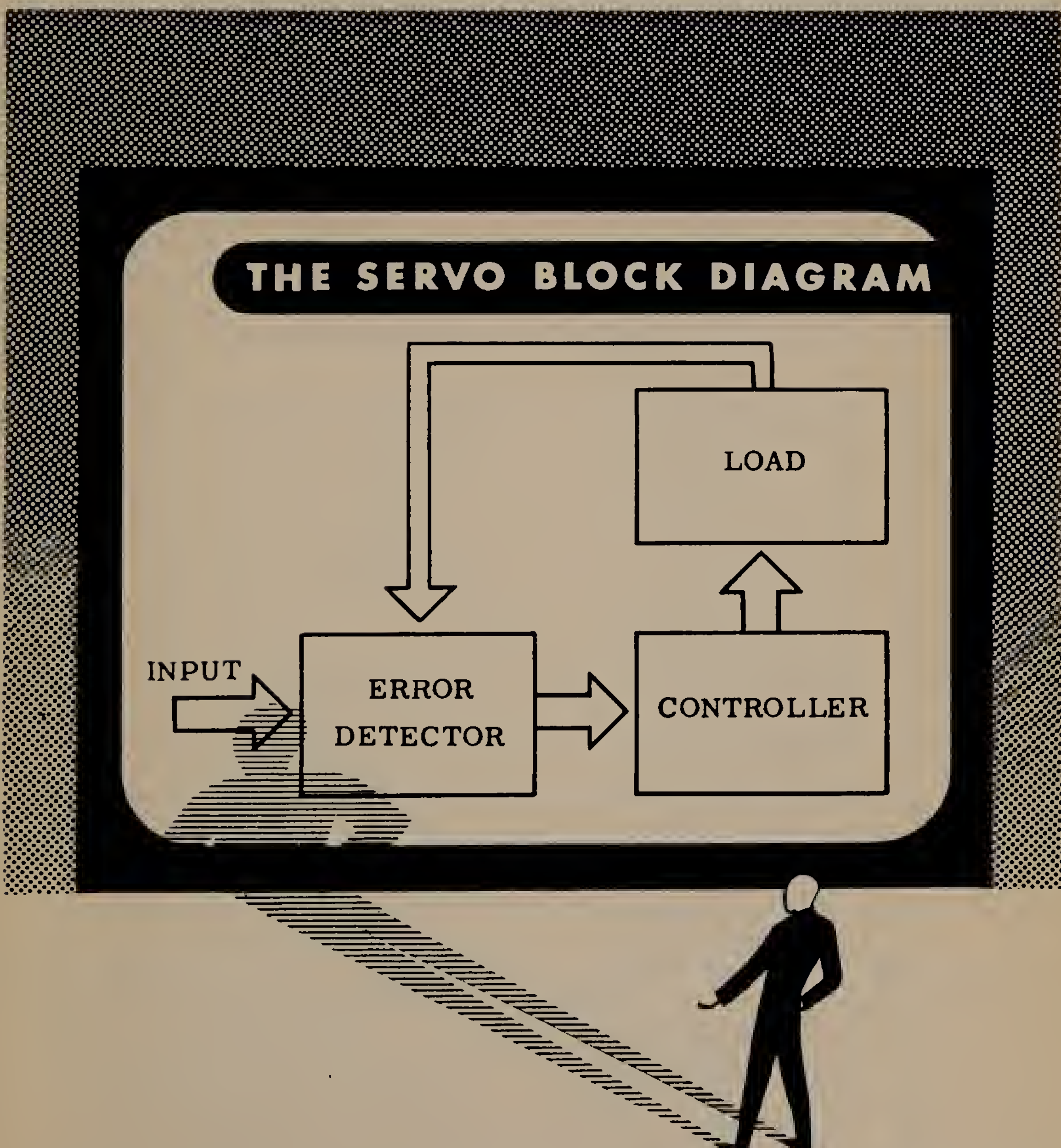
For example, suppose a ship has a true bearing of 30 degrees, and the transducer is trained on an object which has a relative bearing of 40 degrees. If there is a 15-degree change in ship's course to 45 degrees true bearing, the ship's gyro transmits the 15-degree change in course to its synchro generator, which in turn produces the 15-degree change in the rotor field of the DG. This 15-degree shift is transmitted through the servo system, and the transducer is automatically shifted 15 degrees to the left so that it once again trains on the object



The Component Systems

The two servo systems that you have briefly examined are examples of positioning type servos which find extensive application.

The positioning servo as well as the rate and calculating servos are all made up of two basic systems which work together to enable the servo to meet the five basic servo requirements as outlined previously. Once again, the two component systems are the error detector and the controller. The diagram illustrates the component systems in block diagram as they exist in any servo system.



Volume 2 will concern itself with a comprehensive analysis of these two systems—what they consist of, how they work and how they perform their jobs as part of a servo system.

INDEX TO VOL. 1

(Note: A cumulative index covering both volumes in this series will be found at the end of Volume 2.)

...nburgh, Nooger and Neville, inc.

... Synchros and servo-
mechanisms